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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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Flight Vehicle Development Time and Cost Reduction

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.424

FLIGHT VEHICLE DEVELOPMENT TIME AND COST REDUCTION

Copies of Papers presented at the Flight Mechanics Panel Symposium held in E.N.S.A.E., Toulouse, France, from 11 to 14 May 1987.

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PREFACE

The time and cost of developing new military systems are increasing. This is appropriate because the capabilities of the vehicles are also increasing. But the perception is that time and especially the cost of the new systems are increasing at an ever accelerating rate that is greater than the rate of improvement of the capabilities of the machines. If program costs continue to escalate, not only will our defence posture be jeopardised, but the cost of development itself will limit our technology because of the reduced number of times that we can exercise that technology.

Because of its significance, it was deemed appropriate to provide a forum to identify and discuss the elements that contribute to the increased time and cost of development, and to explore the question of what can be done to arrest and reverse the trend. This was the purpose of the Symposium.

During the Symposium it was confirmed that system development time and cost growth is a significant problem and a real threat to our common defence and technology extension. Time and cost savings emanating from technology advancements are shown to be in place and in some cases being used. The major benefits of the technology advancements are cost avoidances and schedule improvement due to the early identification and resolution of problems. Direct savings associated with the technologies are often negated by increased demands for more data, tests, and analyses. The primary areas to seek redress of time and cost growth are in the definition of requirements and the decision-making processes. Changes in requirements were noted to escalate costs significantly. It was noted that others in the more nontechnical areas must come to the forefront and implement solutions to the excessive requirements and decision-making delays. Unless we take positive steps in this regard, we are destined to lose not only our technical edge but our joint capability for defence. Improvements in these areas can be achieved by the following:

- Establish firm, minimum requirements early in the program. Impose restraint in establishing requirements, data, tests, analyses, etc. Allow more judgement.
- Accomplish programs with the minimum number of people and time and increase focus on making the most of our human assets.
- Reduce decision-making time.
- Avoid trying to get the last ounce of gain from every technology.
- Provide more time in the early portions of the program to assure adequate study of various alternatives and design support tests.
- Expect problems and recognize the possibility that tradeoffs may show that absolute adherence to requirements may not be cost-effective or in the best interest of the program.
- Encourage use of prototypes properly supported by early simulation and design support tests.

It was stated at the onset that one of the purposes of this Symposium was to encourage others in the nontechnical area to join with the technical people in attacking the problems resolutely. Whether or not we have been successful in this, only time will tell. But it is believed that the meeting was successful in focusing attention on the situation, showing what our technologies can do to reduce development time and cost growth, and by highlighting key areas that must be addressed to reverse the trend. Significantly, the importance of the problem was recognized by the technologists at the meeting in every area of technology represented. The final recommendation of the Symposium was to make sure that our military and government leaders get this message.

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The Flight Mechanics Panel wishes to express its thanks to the French National Delegates to AGARD for the invitation to hold this meeting in Toulouse, France and for the facilities and personnel which made this meeting possible.

Le Panel du Mécanique du Vol tient à remercier les Délégués Nationaux de la France près de l'AGARD de leur invitation à tenir cette réunion à Toulouse, France; ainsi que pour les installations et le personnel mis à sa disposition.

CONTENTS

CONFERENCE D'INTRODUCTION DE L'INGENIEUR GENERAL FLEURY

Je voudrais d'abord dire combien je suis honoré de prendre la parole devant une assistance de si haute qualité, et aussi féliciter le panel de mécanique du vol d'avoir organisé ce symposium consacré à la réduction des délais et des coûts de développement des véhicules aériens.

Je sais que celà n'a pas été facile, et je peux d'ailleurs témoigner, en tant qu'ancien délégué national à l'AGARD, que lorsque cette proposition a été présentée pour la première fois au Conseil, elle n'a soulevé un grand enthousiasme, probablement parce que le sujet ne ressemble pas à ceux traités habituellement par l'AGARD, et passionne peut-être moins les scientifiques et les ingénieurs que les sujets purement techniques.

Les membres du panel FMP, et tout particulièrement Monsieur Robert LYNN, n'en ont que plus de mérite d'avoir persévéré, et finalement réussi à organiser ce symposium qui devrait aider les responsables de programmes aéronautiques à faire face à l'évolution inquiétante des délais et des coûts.

Ceux-ci paraissent en effet croître aussi irrésistiblement que l'entropie de l'univers, et il est important d'analyser ce phénomène et de chercher à l'arrêter, ou au moins à le ralentir.

Or, son analyse, qui implique d'abord sa mesure, est loin d'être simple. Je ne crois pas inutile d'en rappeler les principales difficultés, car elles ne sont pas toujours perçues par les non-spécialistes, notamment par certains décideurs de haut rang.

D'abord, il faut bient préciser de quoi on parle: pour un délai, quels en sont le début et la fin, pour un coût de quoi, pour qui, et parfois, comment.

Or, comme vous le savez bien, les frontières du développement d'un avion ou d'un hélicoptère ne sont pas toujours nettes: si sa fin peut être assez valablement définie par la livraison du premier exemplaire de série, il y a toujours, dans ses débuts, des travaux plus ou moins exploratoires dont on ne sait pas trop s'ils en faisaient déjà partie ou non.

Et surtout, faut-il y inclure ou non les développements des composants comme le moteur, l'avionique, les armements, etc. dont certains peuvent être au moins aussi longs et coûteux que le développement de la cellule et l'intégration d'ensemble? En fait, il n'y a pas de réponse satisfaisante, et on saura mal, par exemple, comparer valablement un avion dont le moteur a été conçu pour lui et un autre muni d'un moteur existant ou dérivé.

Une deuxième source de difficultés concerne les coûts, mais non les délais. En effet, une semaine est une semaine pour tout le monde et à toutes les époques, mais ce n'est malheureusement pas le cas pour un dollar ou un franc.

Aussi les comparaisons de coûts, et même la simple mesure du coût d'un travail si celui-ci a duré plusieurs années, nécessitent-elles ce qu'on appelle des corrections de conditions économiques et monétaires.

Je ne vous importunerai pas en décrivant ces corrections, mais il faut savoir qu'elles sont moins simple qu'on ne croit généralement, et que l'on peut commettre des erreurs non négligeables.

Je glisserai pudiquement sur les difficultés que l'on rencontre pour recueillir des informations valables sur un sujet aussi commercialement sensible que les coûts, et j'en arrive à la délicate question des performances.

Vous aurez certainement remarqué dans le thème du symposium la phrase "On a l'impression que la durée, et encore plus le coût, des nouveaux systèmes, augmentent à un taux sans cesse accéléré et qui est plus élevé que celui de l'amélioration des capacités des appareils". Que veut dire exactement cette phrase? Peut-on déterminer le "taux d'amélioration des capacités?"

On sait bien qu'en fait, entre un appareil et son successeur, beaucoup de caractéristiques auront changé. Deux intercepteurs, par exemple, pourront différer par la vitesse et l'altitude maximales, le temps de montée, l'autonomie de vol, la portée radar, le nombre de missiles emportés, la manoeuvrabilité, le nombre de cibles suivies, etc. De plus, les missions mêmes seront parfois assez différents. Par exemple, un bombardier classique à haute altitude pourra être remplacé par un avion pénétrant à basse altitude et muni de missiles air-sol.

Pour traduire cette évolution complexe par un coefficient unique, on devra, pour chaque grande catégorie d'appareils (chasse, bombardement, transport, patrouille maritime, hélicoptère tactique, hélicoptère anti-chars, etc.) choisir un certain nombre de paramètres considérés comme les plus importants et les combiner et pondérer dans une formule définissant un "indice global de performance", dont on comparera l'évolution à celles des coûts et des délais.

Bien entendu, le choix des paramètres et des formules sera toujours discutable, d'autant qu'il y a des appareils polyvalents qu'on a du mal à classer, et on sera pratiquement obligé de négliger de nombreux facteurs dont les améliorations sont pourtant indéniables: maintenabilité, capacité tous temps, furtivité radar, contre-mesures, etc.

Ceci dit, comme de toute façon il ne faut pas compter sur une grand précision, on peut quand même, si on dispose d'informations valables en nombre suffisant, se faire une idée approximative de la croissance comparée des performances, des délais et des coûts.

Des études, menées en France par la Direction des Constructions Aéronautiques, semblent indiquer qu'à égalité de masses à vide équipées, les performances, les coûts de développement et les coûts de série augmenteraient à peu pres au même taux, de l'ordre de 5% par an. Les délais de développement croîtraient moins vite, peut-être de 2% par an.

J'ai suffisamment insisté sur les difficultés de mesure du phénomène pour que ces indications soient prises avec beaucoup de réserves, d'autant qu'il y a peu de points pour tracer des courbes et qu'ils sont assez dispersés. Pour l'anecdote, je vous citerai deux cas exceptionnels (et peu significatifs) de délais de développement: celui du Concorde peut être évalué à 13 ans et, en 1916, un bombardier quadrimoteur Voisin a été conçu et réalisé en... 35 jours!

Je souhaite que d'autres paticipants à ce symposium, en particulier nos amis américains qui disposent de données plus nombreuses que nous, puissent nous dire si leurs propres études aboutissent à des conclusions analogues, ou au contraire différentes.

J'ajoute que même si les coûts n'augmentent pas plus vite que les performances, celà ne doit pas nous rassurer, et encore moins nous inciter à l'inaction. Car dans aucun des pays de l'Alliance les budgets militaires n'augmentent durablement de 5% par an en valeur réelle. Nous somme donc de plus en plus contraints, non seulement de réduire les quantités d'appareils commandés, mais aussi, à cause du poids relatif croissant des dépenses de développement, d'étaler ces derniers dans le temps en différant le renouvellement des flottes.

Vous connaissez tous le calcul d'extrapolation selon lequel même les Etats-Unis ne pourraient plus bientôt se payer qu'un exemplaire d'un nouvel avion. Il ne doit évidemment pas être pris à la lettre, car on fera forcémment des choix différents. En revanche, pour les développements, nous voyons bien dès aujourd'hui que beaucoup de programmes sont lents à démarrer pour de pures raisons budgétaires, et aussi que des pays comme le Royaume-Uni et la France ont dû renoncer, par exemple, à financer le développement d'un système de détection aéroporté.

Dès lors, que faire pour éviter, ou au moins ralentir, cette évolution implosive des programmes aéronautiques, si l'on ne peut ni augmenter les budgets, car les produits nationaux bruts ne croissent pas assez vite, ni renoncer à la course aux performances à cause de la menace militaire, ou de l'appel du marché civil.?

Une première voie est celle de la coopération internationale, qui permet de partager le coût des développements. Elle se pratique depuis bon nombre d'années, mais avec des fortunes diverses, car la conciliation des exigences différentes des partenaires allonge les délais et engendre des surcoûts qui vont parfois jusqu'à dépasser l'économie due au partage. Mais peut-être n'est-ce là qu'un rodage un peu long et apprendrons-nous enfin à coopérer plus efficacement?

Une autre idée serait de compenser les hausses par des économies sur d'autres rubriques budgétaires, notamment sur les coûts d'utilisation et de maintenance, que les progrès, en fiabilité, en ergonomie et en maintenabilité devraient logiquement faire décroître. C'est ce que cherchent à estimer et à concrétiser les études de Coût Global de Possession (Life Cycle Cost).

Mais la voie le plus intéressante est évidemment de réduire les délais et les coûts en agissant directement sur les tâches mêmes, dont les développements sont constitués.

Peut-être penserez-vous d'ailleurs que c'est la seule chose qui compte, et que j'aurais mieux fait de commencer par là au lieu de parler de l'analyse du phénomène, car il est utile de soigner les maladies que de les décrire.

Sur ce point, mon opinion est un peu plus nuancée, car on soigne quand même mieux la maladie quand on en a compris les causes et les mécanismes. D'autre part, l'analyse des coûts et délais passés constitue une base indispensable, bien qu'insuffisante, pour de bonnes estimations des coûts et délais des programmes à lancer, et je ne crois pas que l'on puisse les optimiser si on les a mal estimés au départ.

Quoi qu'il en soit, je suis bien d'accord sur l'intérêt essentiel des actions de réduction directe des travaux de développement. Si j'ai choisi de ne pas en parler beaucoup, c'est simplement parce que ce sera fait par des orateurs plus qualifiés que moi tout au long du symposium. Comme vous l'aurez vu à la lecture du programme, la plupart des exposés y sont consacrés, surtout dans les deuxième et troisième sessions, concernant respectivement les aspects techniques et de gestion, mais en partie également dans la première, qui a trait, me semble-t-il, à la construction générale des programmes de développement.

Les aspects techniques sont les plus spectaculaires, en particulier grâce aux énormes progrès de l'informatique. Ainsi par exemple la Conception et la Fabrication Assistées par Ordinateur ont-elle permis d'automatiser des travaux qui nécessitaient, il y a peu d'années, des heures et des heures de dessin et d'usinage plus ou moins manuels. Ainsi peut-on obtenir aujourd'hui par des simulations sur ordinateur des résultats qui exigeaient auparavant des essais en soufflerie et en vol, longs, couteux, et même dangereux.

Mais les actions d'organisation et de gestion méritent aussi un examen attentif. Elles impliquent bien sûr la bonne utilisation des outils de gestion classiques tels que l'organigramme des tâches (Work Breakdown Structure), les réseaux PERT (Program Evaluation Review Technique), les systèmes de maîtrise des coûts et délais (Cost Schedule Control System), etc., mais soulèvent aussi des problèmes plus délicats comme le rôle et le bon choix des modèles probatoires, le nombre de prototypes, la sensibilité aux spécifications, et bien d'autres dont il vous sera parlé, notamment tout à l'heure par le Docteur GANSLER.

Il faut souligner que ces problèmes ne sont pas entre les seules mains des industriels réalisateurs des matériels, mais impliquent fortement les utilisateurs, et bien entendu les services qui mènent le programme et négocient les contrats. Et de même que dans les fabrications on considère le triptyque coûts-délais-qualité, il faut tenir compte dans les actions de réduction des coûts et délais de développement d'un troisième volet, que l'on pourrait appeler assurance d'aboutissement. Par exemple, dans les clauses techniques contractuelles, on pourra hésiter entre une garantie absolue de performance, que l'industriel n'acceptera que moyennant un prix forfaitaire plus élevé, et des clauses plus souples, moins coûteuses, mais qui laisseront un risque de travaux supplémentaires pour atteindre effectivement les performance nécessaires.

L'expérience apprend d'ailleurs que les deux solutions sont âprement critiquées ... après coup.

Nous aurons donc de nombreux exposés qui nous montreront les grands progrès déjà réalisés et, j'espère, les voies de nouveaux progrès à venir. Ce qui est sûr, c'est que de nouvelles réductions de coûts et de délais ne se feront pas toutes seules. Des efforts opiniâtres devront être accomplis par tous les acteurs, et les incitations de natures variées pouvant contribuer à leur motivation sont certainement aussi un sujet à creuser.

Je suis certain que le symposium qui commence aujourd'hui contribuera à faire mieux apprécier les efforts et les progres et à en susciter de nouveaux. Il serait heureux, aussi, que l'AGARD donne l'exemple d'échanges fructueux d'informations, dans ce domaine que nous savons difficile et assez sensible.

KEYNOTE ADDRESS
TIME AND COST REDUCTIONS IN FLIGHT VEHICLE ACQUISITIONS

by

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The subject of this symposium -- reducing schedule and cost in the acquisition of future systems -- is an absolutely crucial one for all NATO countries. The trends (as will be shown) have clearly been adverse. Thus, as we enter a new era of next-generation systems, combined with that of a period of fiscal austerity, unless these historical trends are reversed -- particularly the incredibiy high unit production costs -- future systems will simply be unaffordable. Additionally, with the rapid evolution in technology (for example, electronics production lines that become obsolete within a six-month period) nations will be developing systems -- over a twelve to fifteen year acquisition cycle -- that are no longer technologically useful; even if they could be afforded. Clearly, something must be done.

THE HISTORICAL TRENDS:

The principle focus of this paper will be on the characteristics of the needed changes to improve the acquisition process over the coming years. However, first we must answer the basic questions "is it taking longer and costing more? and, if so, what are the major factors effecting the cost and schedule growths?" In 1982 the US Air Force Systems Command undertook a study to answer these basic questions. They looked at over 109 programs -- acquired during the last three decades -- and interviewed an extensive number of industry and government executives. The data in Figure 1 shows the results of this study, in terms of the increasing development time of systems. (Here, development time includes pre-full-scale development activities that are directly attributable to a particular program; and it is assumed that the development ends at the first production article delivery.) As can be seen, the long-term trends -- of increasing development time -- are quite clear. While it varies for different types of systems, there are no categories in which the development time has gotten shorter. (It might be noted that for fighter aircraft the full-scale development time tended to stay about the same, but the overall development time stretched; due to increasing pre-full-scale development efforts.)

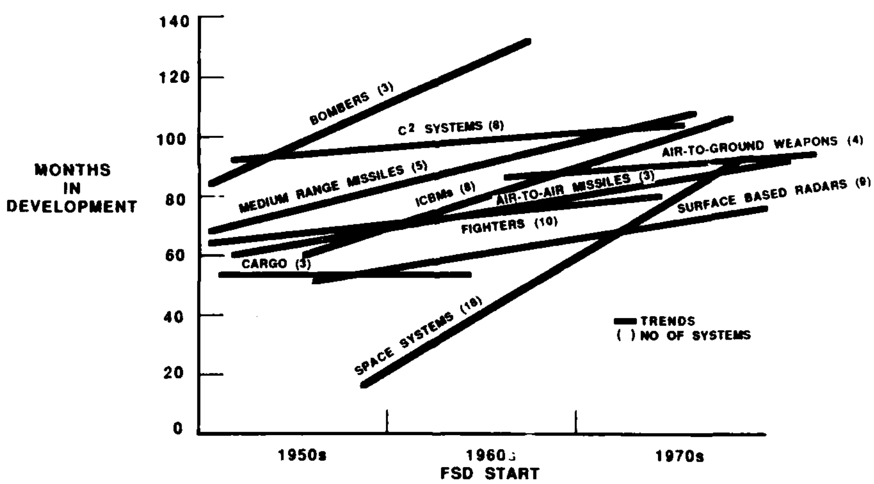

Figure 1 - Development Time (Statistical Trends)

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What is particularly important to note is that this increasing development time has gotten worse for systems currently under development -- as shown by the examples in Figure 2 (from that same study).

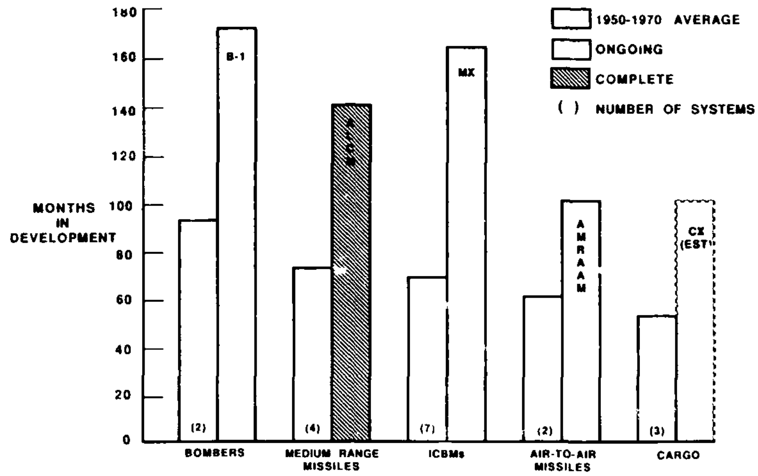
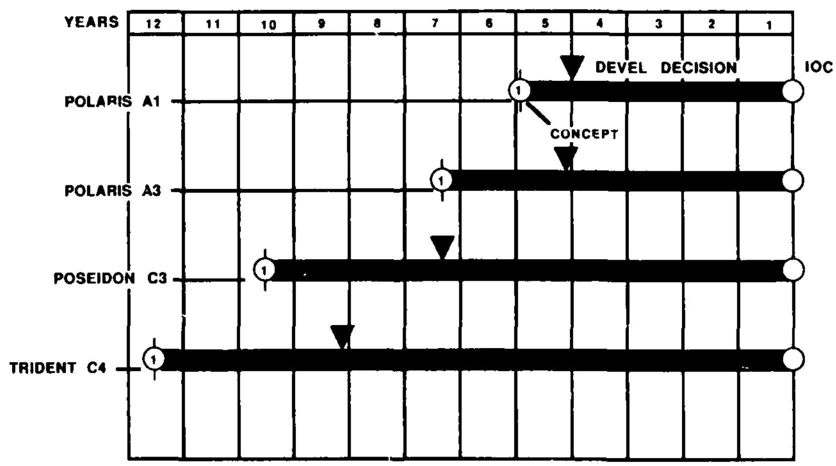


Figure 2 - Development Time (Relative Comparisons)

These characteristics are, of course, not unique to the Air Force, as Figure 3 shows for the Submarine Launched Ballistic Missile (SLBM) development programs of the Navy. In general, it appears that where it used to take five to six years to develop a system, today it takes more like eight to ten years (with some requiring even twelve to fifteen years).



IOC = Initial Operational Capability

Figure 3 - Submarine Launched Ballistic Missile System Acquisition

Turning to the cost side, the important parameter to consider here is not the development cost itself, but rather the total program unit cost (defined here as R&D costs plus production costs divided by the number of production articles; and presented in constant-year dollars). Clearly, we might want to spend a little more money in the development phase <u>if</u> it could result in a considerable reduction in the far-larger dollars spent in the production phase. (This cost trade-off is a common commercial

practice, but it has rarely been used in government development programs because "up-front" money is always so hard to obtain.) Figure 4 shows some examples of aircraft total unit cost growths that have occurred in the past.[3]

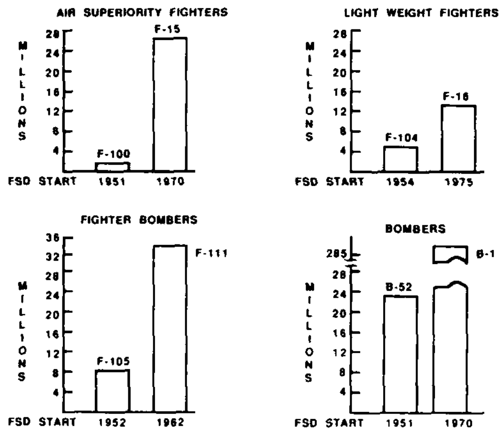


Figure 4 - Aircraft Costs (Total Program Unit Cost - FY81 Dollars)

Attempts have been made by various studies to aggregate all fighter aircraft into a constant dollar, constant quantity data base and the data invariably looks like that shown on Figure 5, which indicates an approximately seven percent per year compound cost growth from generation to generation of fighter aircraft. (Other studies -- depending upon assumptions made, particularly about inflation, quantity adjustments and differences in evolutionary system performance -- tend to put this growth down to as low a level as five percent per year, while others go well over the seven percent per year; however, they all have essentially the same exponential cost growth characteristic.) Importantly, studies of performance on these same aircraft have shown a similar, exponentially-increasing growth . These indicate that from generation to generation of weapon systems the performance improvements have been in the range of five percent per year. Thus, depending upon the assumptions made for both the cost and performance analyses, the data indicates that we appear to be getting performance growth equal to, or almost equal to, the cost increases that we have been seeing. Nonetheless, we are paying a severe penalty for this cost increase; in terms of the quantities of systems we can afford to buy. For example, the US bought in the range of 3,000 fighter planes per year in the 1950s, around 1,000 per year in the 1960s, and around 300 per year in the 1970s. Only the dramatically increased budgets of the last five years have allowed us to buy a similar quantity -- of around 300 per year -- in the first half of the 1980s. Thus, we are getting better and better performance out of each individual system, but buying fewer and fewer of them. The logical extension of this trend is certainly unacceptable.

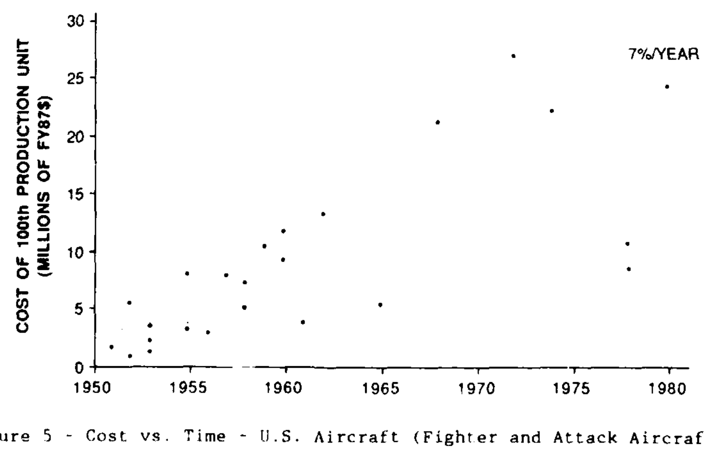


Figure 5 - Cost vs. Time - U.S. Aircraft (Fighter and Attack Aircraft)

To understand what can be done about reversing these trends, one must turn to an analysis of their causes. Again, the 1982 Air Force study found the data shown in Figure 6. Essentially, it said that in the analysis of a large number of major Air Force developments the causes of schedule and cost growth in the pre-1970 time period was primarily driven by technical problems and technical advances; while in the more recent era these technical issues have been more than matched by growing management problems. Particularly by program instabilities -- often caused by forces (e.g., budget changes and "requirements" changes) outside of the program manager's control. The results of this analysis were recently confirmed by a similar study of a significant number of US Army development programs. Here it was found that changing requirements dominated the causes of program stretchout and cost growth.

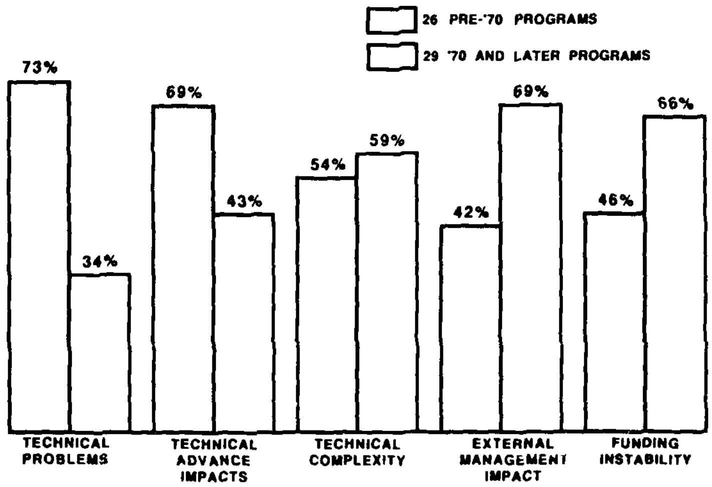


Figure 6 - Trends in Major Factors Effecting Cost and Schedule Growth

NEEDED ACQUISITION CHANGES:

Given the above-described increasing cost and schedule trends, and the simultaneous need for increased quantities of systems, it is clear that a rather dramatic change in the acquisition process must take place. Over the past year, significant steps have been taken in this direction in the US. Noteworthy among these efforts were the President's implementation of the recommendations of his Blue Ribbon Commission on Defense Management (chaired by former Deputy Defense Secretary David Packard), the Goldwater-Nichols Defense Reorganization bill and the acquisition legislation contained within the 99th Congress' authorization and appropriation bills (issued at the end of 1986).[9] The focus of a major share of these changes in the acquisition process were on the "front end" of the process, i.e., changes in the requirements, budgeting, and planning process; and changes in the early portion of the system's development process. As shown by the data on the lower portion of Figure 7, a very small percentage of a program's total dollars are spent prior to the initiation of full-scale development (FSD), while the overwhelming majority of the dollars are spent in the production and support phases. Nonetheless, an incredibly large share of the total life-cycle cost of a system are "designed in" prior to the initiation of full-scale development. As shown by the top curve in this figure, something like 85 percent of a total program's cost are designed in by that point -- but only about three percent of the actual dollars have been expended. Major decisions, such as "should an aircraft have one or two engines?" will determine the lion's share of the production and support dollars downstream, but are made before the system even enters full-scale development. Thus, the broad management concept for improving the acquisition of new systems must be to increase the focus on the front end. Then, having done the best possible job to "freeze the design," go rapidly through the development and production phases.

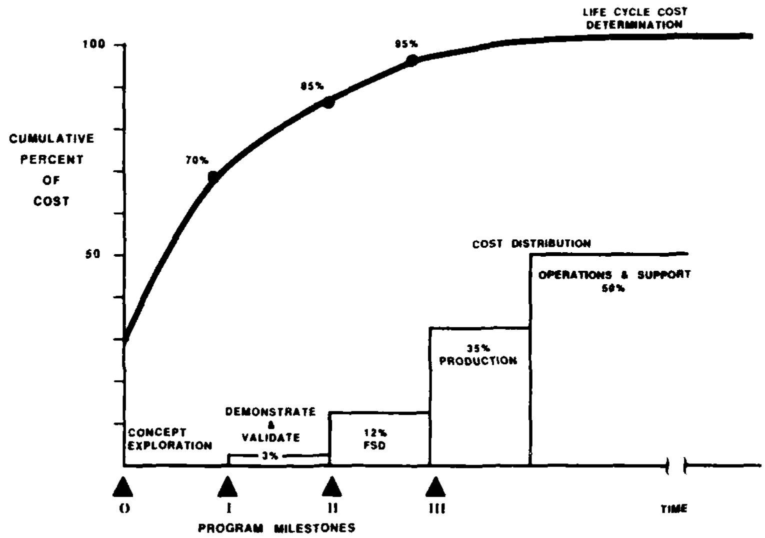


Figure 7 - Early Efforts Determine Life-Cycle Cost

In the "Packard Commission" report on the acquisition process they approached the question of "how to improve the acquisition process?" by looking at "successful" major systems developments -- in both the commercial and government arenas (rather than taking the normal route of looking at what went wrong on problem programs). They came up with a set of eight critical management issues which must be addressed on all future developments, if we are to reverse the adverse historical cost and schedule trends. Namely:

- <u>Short and stable schedules</u> (for development and production)
- <u>Experienced, small staffs</u>, with <u>clear command channels</u> and <u>limited reporting</u>
- Good <u>communication with users</u>
- Presence of a <u>continuous alternative</u>
- <u>Cost realism</u> (for both development and production) and <u>unit production cost as a significant design requirement</u>
- <u>Prototyping</u> (for both cost and performance) and <u>early and extensive testing</u>
- <u>Planned product improvements</u> and maximum use of <u>"proven" components and subsystems</u> (especially commercial items)
- Early <u>development phase funding for production and support</u> considerations.

This is <u>not</u> a list of typical characteristics found in most US Government development programs. Rather, the typical program contains almost the inverse of each of these. Nonetheless, these are the areas currently receiving increased attention within the US -- in the management of major systems' developments. Thus, the remainder of this paper will focus on these eight, interrelated -- and all badly needed -- acquisition initiatives.

1. <u>Short and Stable Schedules</u>

All of the successful programs studied began by using previously-demonstrated technology (see number 6 below) and by realistically estimating their program costs (see number 5 below). They then fully-funded the necessary dollars and maintained the program's initial "requirements" throughout the program's development. This combination -- of demonstrated technology, cost realism, and stable budgets and requirements -- allowed them to achieve extremely short development and production schedules. Thus, they realized maximum economic efficiency and got the new systems fully deployed in the fastest possible time. (Thereby addressing both the budgetary and military needs most

effectively.) In looking at other -- more typical -- government programs, it can be observed that these often also plan a relatively short development and production program, but almost invariably they are forced to stretch it out -- because of technical problems, inadequate dollars or changing requirements. In all cases, this stretchout of programs has been found to be prohibitively expensive. Citing but one example, on the F-15 program an efficient production rate had been planned, but when the program was subsequently stretched out -- for three extra years -- it increased the cost for the same number of airplanes (ignoring inflation effects) by over $2 billion. Thus, the Air Force lost more than 83 aircraft that could have purchased for the same number of dollars. Similar dramatic impacts are found from stretching out development programs; since the majority of the labor costs (e.g., management, engineering, etc.) remain on the program and charge at a monthly rate. Therefore, "the longer the program, the higher the cost."

To achieve shorter, more stable schedules, the DoD has been moving to a concept of "baselining" all major weapon systems, i.e., with the Service "signing up" to long-term realistic prices and technical requirements, and then sticking to them in their budget and planning processes. To be successful, however, these programs must also incorporate all of the following actions as well.

2. Experienced, Small Staffs with Clear Command Channels and Limited Reporting

In a typical US Government program, the senior managers frequently are quite inexperienced and often rotate a number of times during the development phase of a program. (For example, one study showed that the average experience of an Army program manager was less than two years of total acquisition experience.) Often, this inexperience is compensated for by having a relatively large staff of people, all responsible for small pieces of the overall activity. This problem is further compounded by having a very large number of "layers" above the program office, through whom all decisions must be passed. (For example, in a typical Department of Defense activity a program manager may have to "sell" between 20 and 40 other managers -- both horizontally and vertically -- in order to get a decision made on the program; and many of these people, similarly, have had little or no acquisition experience.) Such a decision-making process, obviously, greatly stretches out the program. In fact, one estimate was that on a seven-year development program over three and a half years of the time was taken up with "decision-making" -- and the rest with actual development. It is not at all uncommon, in a Department of Defense development program, for a six-month period to be required prior to a major milestone decision being made and implemented. (This, of course, is not in parallel with the program's progress; since the decision process requires that all of the test results be in, prior to addressing the issue.) Finally, it is estimated that something like 20 percent of a typical DoD development program's cost is devoted to "reporting" on the program ("supplying data"). By contrast, in those programs that were successfully run (particularly in the commercial world) the primary reports required were "deviation reports," in which thresholds were established for cost, schedule and performance and, as long as the program stayed within these limits, very little reporting was required.

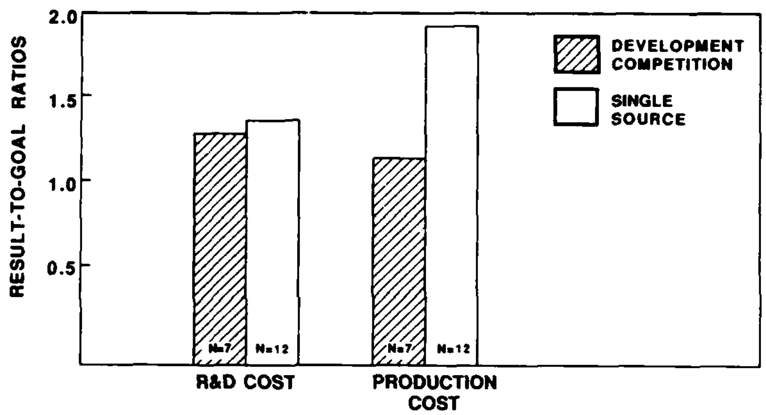
3. Good Communication with the Ultimate Users

There's a myth that exists within the acquisition world -- and often even perpetuated in the schools that teach acquisition -- that there is an initial "requirement" established for a system, and then this is turned over to the development community to pursue. By contrast, on a successful program it is recognized that there must be a continuous trade-off made between the user and the developer -- in terms of the impact of varying requirements on development and production costs and schedules. Once it is recognized that, realistically, a program is "budget-constrained" and must operate within an overall program dollar ceiling, then the user is essentially making trades between the quantity and quality of the systems that must ultimately be procured. This is a particularly important relationship, since the user typically does not view himself as resource-constrained, but he does care about how many systems he ultimately obtains. Thus, a successful program has the user continuously involved with making the day-to-day trade-offs that crop up during the development phase, and allowing "flexibility" in some of the technical parameters that might prohibitively drive up system costs (see number 5 below for a more extensive discussion of this cost/performance relationship).

4. Presence of a Continuous Alternative

What makes a market economy operate effectively is the continuous presence of an alternative for the buyer -- such that, if a supplier reduces his quality or raises his price, the buyer can go elsewhere. Unfortunately, the typical program in defense acquisition has no such alternative present. Rather, we usually have a fierce competition for the initiation of a development program (often referred to as the "auction") and this is followed by a sole-source environment throughout the many years of the development and production phases of the program. Occasionally in the past, the presence of continuous competition -- in the development and/or the production phase -- has been tried, and the results have been very impressive. As shown by the data in Figure 8, for those programs that had "dual sourcing" during the development phase of a set of Army programs, the R&D costs were better controlled; however -- most importantly -- the

production costs were dramatically reduced as a result of the competitive development phase; thus, far more than justifying the increased development cost for the second source. Equally significant, it was found that, on the average, the performance was much higher on those programs that had been dual sourced than those that had been single sourced. (In one program it was found that only the second source could complete the job successfully.) The whole nature of a development program changes when continuous competition is introduced, because it gives the government the upper hand in being able to get far more responsiveness out of their dual suppliers. Additionally, it creates the necessary incentives for the suppliers to put their best people on the program and to achieve the stated government objectives of performance, schedule, and both development and production costs. In fact, it was found that when the competition was continued, or even introduced, in the production phase, the presence of the two sources -- continuously competing for an annual share of the business -- resulted in a <u>net</u> overall production program cost savings that averaged 25 to 30 percent (even including the investment cost required for the second source); and, again, quality and performance were found to also be significantly enhanced. As with many of the eight key changes required in the acquisition process, this presence of continuous competition requires an increase in the initial investment (for the dual-sourced development phase of the program, and for the production tooling and start-up of the second source). However, this is more than offset by the better performance, as well as cost and schedule control in the development phase itself; and, particularly, by the dramatic reduction in the production costs that are realized on the program.



*DECEMBER, 84 SARS (SYSTEMS ACQUISITION REPORT SUMMARIES PRESENTED TO CONGRESS)

N = NUMBER OF PROGRAMS

Figure 8 - Army Development Competition vs. Army Single Source*

5. <u>Cost Realism (in Budgeting) and Use of Unit Production Cost as a Significant Development Phase Design Requirement</u>

In order to achieve the critical "program stability" noted in item 1, it is essential that a program realistically budget for development and production costs at the initiation of the full-scale development phase. In this way, it is possible to, first, determine if the program is "affordable," i.e., <u>if</u> the development is successful, will the program be produced within the nation's resources? Second, the issue of cost realism forces the development program manager to address the <u>risk</u> associated with development of the system. Obviously, since the program is starting into development, rather than production, there is -- by definition -- a considerable risk in the effort. Yet, historically, many programs have been optimistically budgeted under the assumption of "zero risk." This use of unrealistic estimates has been a significant cause of the average program's cost growing between 50 and 100 percent during its lifetime (the spread being a function of how one accounts for inflation effects). If "affordability" limits are established for a program before it is designed, then these dollars can be used to control the design itself. (Such an approach -- of affordability impacting the design -- is currently being done on the Strategic Defense Initiative program, wherein affordability is influencing the selection of various system architectures.) The affordability level can be used to establish a unit-production-cost design objective for the system; since if we know the total dollars likely to be available and the quantities required to be purchased to do the job, this determines an approximate, average, unit production cost. That number essentially becomes the "design-to-cost" objective of the program. To see how this can be applied, consider the data in Figure 9. This chart is simply an extension of the one previously shown for the cost of fighter aircraft, but extrapolated out into the time period of the Advanced Tactical

Fighter (ATF) now under preliminary development in the US. If this plane had been specified in the traditional fashion, one would have written a "requirement" for the maximum technological performance that could have been achieved -- or promised -- in the late 1990s time period. Initial estimates, based upon designs for that performance, indicated that each fighter aircraft -- in production quantities -- would cost over $100 million. Thus, it was decided that a design-to-cost approach would be used for this aircraft; wherein an engineering design requirement was placed on the aircraft that, when it went into production, its average unit cost would be $35 million ("Option 2" on Figure 9). Clearly, this ability to move the cost "off of the historical curve" is exactly what is required for the next-generation systems to be affordable; yet it is an extremely challenging engineering job. It is comparable to what the commercial world has been able to realize, for example, in the electronics area, as it moves from one technology to the next and simultaneously achieves dramatically improved performance and dramatically reduced equipment costs.

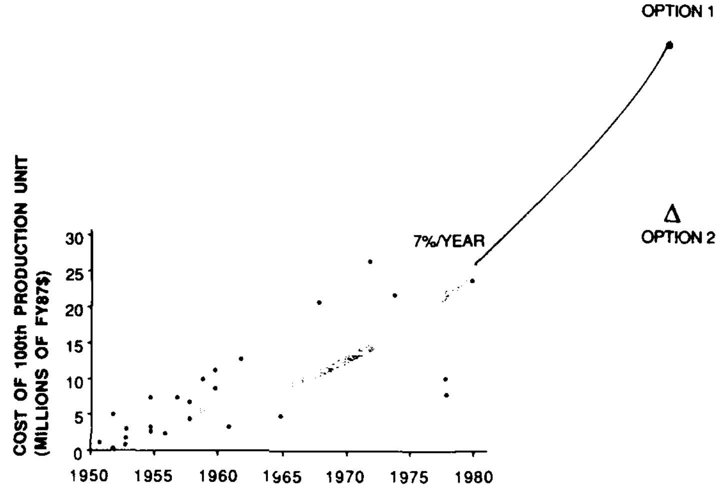


Figure 9 - Cost vs. Time - U.S. Aircraft (Fighter and Attack Aircraft)

For an engineering explanation of how this works, note Figure 10. Here, it can be observed that as we move from the current technology to the new technology we have a choice of taking Option A which is the higher cost, greatly-improved performance, or Option B, the lower cost and almost-as-greatly-improved performance.

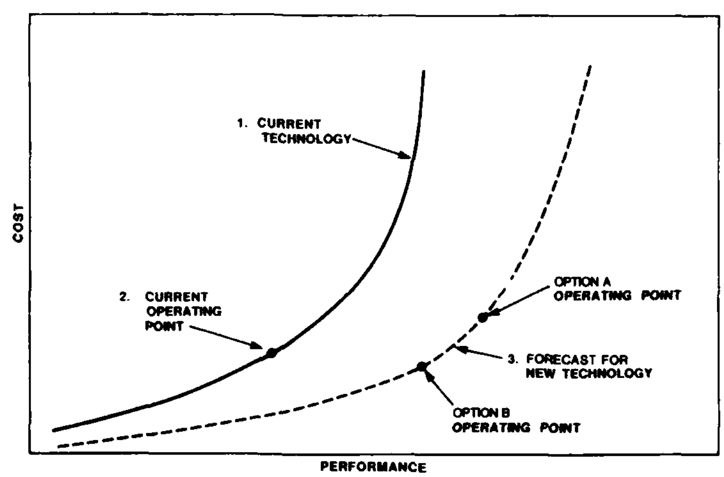


Figure 10 - The Cost/Performance Choice for New Technology

However, there is much more to the story than simply choosing an initial design point, as the data in Figure 11 points out. Here, we see that, after the development has begun, the actual new technology may not turn out to be quite as good as had theoretically been predicted. Thus, we are forced to make a critical design decision; namely, do we hold firm on the performance "requirements" -- as is usually done -- and allow the program development and, particularly, production costs to rise dramatically (as shown in this figure) or do we hold the unit cost as a firm design criterion and allow the performance to fall slightly (while still being dramatically greater than that which the older technology represents). This is the critical quality/quantity trade-off; and it is a design decision which must be made continuously during the evolution of the development phase. It is the principle reason for the close communication being maintained with the ultimate user (as discussed in item number 3 above). Designto-cost is the common practice in the commercial world and it is essential that the government begin to adopt it. In a resource-constrained world, it is the only way we will be able to afford <u>enough</u> of the next-generation systems to effectively perform their military missions.

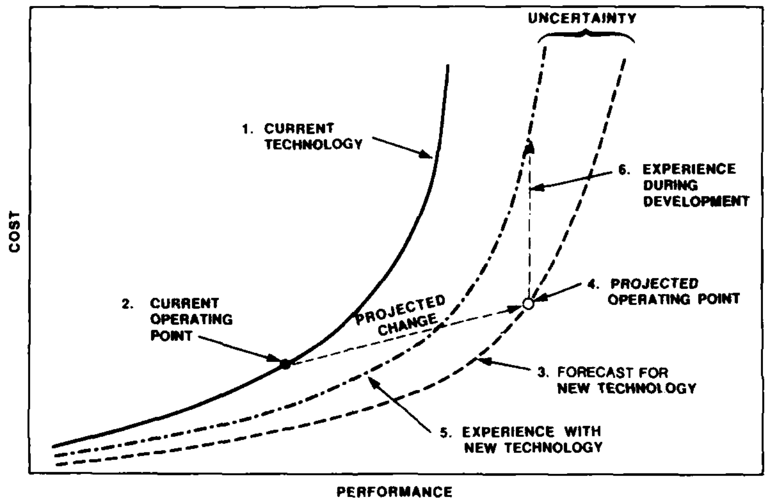


Figure 11 - Impact of Uncertainty on Systems Acquisition Costs and Performance

6. <u>Prototyping (for cost and performance) and Early and Extensive Testing</u>

Prototyping, at both the system and subsystem level, has historically been done; but its primary objective was proving -- technologically -- that something is "possible." Traditionally, the system was then almost totally redesigned during the develonment phase; such that the unit production cost of the system -- as inherent in the design -- rose dramatically during the redesign phase. What is necessary is for the prototyping to be done with a system that is close enough to the ultimate production design such that one is able to make a good estimate of the cost of the ultimate system, and of the performance of that <u>same</u> system. (David Packard has referred to this as "fly before you buy, and know how much it will cost before you buy it.") Through this early prototyping -- at either the system or subsystem level -- it is possible to prove out the necessary next-generation technology prior to the rapid full-scale development described in item number 1 above. Additionally, successful programs have used these prototype systems to do <u>operational</u> testing early on; in order to determine if the system -- when later fully developed and produced -- will, in fact, satisfy the user needs, i.e., will it perform the operational military mission? versus the technical (engineering) "requirement."

After moving out of the prototype phase, unfortunately, history has shown that one of the ways programs have "saved money" (during the development phase) is to reduce the number of test units and the amount of test time. This is another example of short-sighted attempts to save development dollars at the expense of what, ultimately, becomes a stretched out and overrun program. Clearly, if you can't afford to do adequate testing early on, then the program is doomed to problems later.

7. <u>Planned Product Improvements and Maximum Use of "Proven" Components and Subsystems</u>

An interesting point that has been found -- both in Europe and the US -- is that when existing systems are modified, rather than new systems started from scratch,

the time and cost for development are both dramatically reduced (for comparable improvements in performance). For example, as shown in Figure 12, the historical growth curves for aircraft (that were previously shown in Figure 5) were found to actually reverse for the modification programs on the F-4 and the F-15. (These curves are appropriately adjusted back to the equivalent hundredth aircraft for the modification programs, as though they had been new programs.) The concept here is not to start off a new aircraft program assuming that it requires a new set of avionics, a new engine, a new weapon system, etc., but, instead, to independently develop each of these subsystems (with standardized interface specifications so they can be "plugged in" when they are proven) and to insert these upgrades at an appropriate "block point" in the production cycle. (In fact, even a new airframe could be considered a "modification," using this approach.)

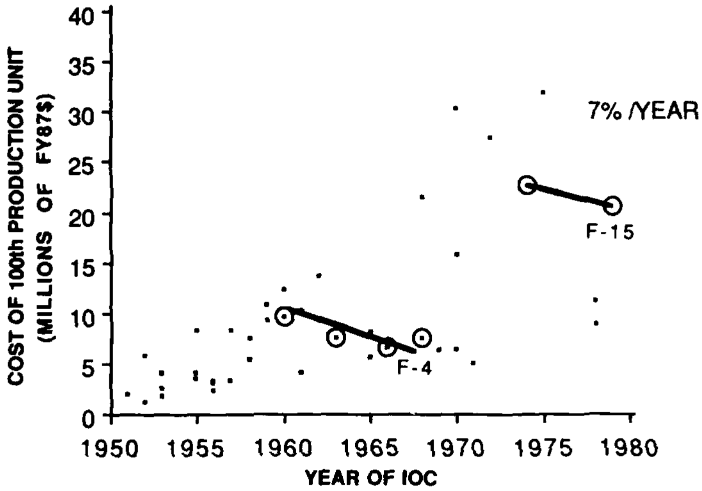


Figure 12 - Cost vs. Time - U.S. Aircraft
(Modification Approach - Fighter and Attack Aircraft)

Consistent with the idea of using proven systems and subsystems is the concept of defense systems making maximum use of commercial subsystems and components. Both the Packard Commission and a recent Defense Science Board Task Force emphasized the dramatic benefits -- particularly with electronics -- that could be achieved through greater use of commercial components. Today, new automobiles have semiconductor devices hard-mounted to their engines. These see environments very similar to that seen by military equipment and for these comparable environments the data shown in the following table compares costs, reliability and leadtimes of the commercial and Mil Spec parts .

		Commercial	Mil Specs
- Part Cost	Bipolar Digital Logic	$1.67	$15.78
	Bipolar Linear	$0.42	$11.40
- Reliability (Failure Index)		0.06	1.9-4.6
- Leadtime for New Part		1-12 Mos.	17-51 Mos.

As can be seen from this table, not only are commercial parts an order-of-magnitude cheaper, but they are also more than an order-of-magnitude more reliable (as a result of the far greater quantity produced and the extensive field feedback data) and they are also available for use in new system's developments years ahead; thus potentially providing a far more rapid development cycle. The Defense Science Board study found that systems built from commercial components would have costs that were between two and eight times cheaper overall, with comparable or better reliability; and that these systems could be acquired between two and five times more rapidly -- as a result of using off-the-shelf, proven commercial components. Since most defense equipment today tends to have between one-third and one-half of its costs devoted to electronics, a shift of this sort could make a dramatic difference in both cost and schedule for future systems' development and production. What is required is for the government to learn how to buy these commercial systems and components -- within its existing procurement operation. Steps in this direction are now being initiated within the US.

8. Early Development Phase Funding for Production and Support Considerations

Traditionally, the development phase of a new system focuses almost exclusively on that phase. Then, later, we find out how much it will cost to produce and maintain it. However, this is inefficient -- in both time and dollars -- particularly with current trends towards new, computer-integrated manufacturing technologies. If funds are available -- up-front -- to include production considerations as part of the original design job, then one can make the transition from computer-aided design (CAD) through computer-aided manufacturing (CAM) and into computer-aided logistics (CAL) in a smooth and continuous process. In fact, the overall shift towards computer integrated manufacturing (CIM) promises incredible benefits for reducing development time and cost; as well as great savings in the production and subsequent support of future systems. This clearly represents a major cultural change for the typical high-technology, defense development program. It requires a concept of an engineering/production/support team -- in the early design phases -- that is more than simply the lip service that has traditionally been given to this area. It requires that the design be continuously modified in order to take producibility and maintainability directly into account -- throughout the design effort. This, too, is likely to increase the cost of the development phase, since it introduces multiple iterations into the design -- as well as added people. However, it means that, as designed, the system will be producible; and thus the leadtime for the overall development time -- from initiation of the effort through first production unit -- should be dramatically reduced and the cost of the system, in production, similarly dramatically reduced.

CONCLUSION:

As discussed within each of the above eight areas, these actions are highly interrelated. In fact, it would be wrong to do some of them without doing others. For example, we certainly wouldn't want to eliminate management layers unless we had people with experience running the programs; or, there is no point in attempting to achieve program stability if you have begun the program with unrealistic schedule and cost estimates. Thus, what is required is an integrated effort -- focused primarily on the front end of the program -- in order to achieve the needed overall changes.

Recently, efforts have been initiated within the U. S. Government -- both by the Congress and by the Executive Branch -- to attempt to make the overall "cultural change" that would be required to effectively implement these significant changes. It will be a long and hard "battle"; with an enormous amount of institutional resistance to be overcome, within a large and bureaucratic system -- both on the government and industry sides. Nonetheless, the adverse historical trends in schedule and cost (discussed at the beginning of this paper) clearly must be reversed in the future. Our nation's security requires it and the taxpayers deserve it -- so we must succeed.

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2. Defense Science Board Summer Study, 1976.

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4. For example, TASC's TASCFORM methodology: E. Cherniavsky and LTCOL E.T. Timperlake, USMCR, "Implications of Tactical Air Cost and Performance Trends," Defense Management Journal, 3rd Quarter 1986.

5. Army Affordable Acquisition Approach (A^3) Final Briefing, Army Materiel Command, Washington, DC, September 24, 1985.

6. Interestingly, when one looks at US programs involving multi-service management, e.g., the F-111, or European programs involving multi-national management one finds that the difficulties of maintaining stability in the requirements and budget processes are even more difficult, and thus the impact on schedule and cost growth even more dramatic.

7. President's Blue Ribbon Commission on Defense Management, A Quest for Excellence: Final Report to the President, June 1986.

8. Goldwater-Nichols Department of Defense Reorganization Act of 1986, Public Law No. 99-433, 100 Stat. 992; September 12, 1986.

9. 99th Congress Authorization and Appropriations Bills (Report 99-718, July 25, 1986 and Conference Report 99-1005, October 15, 1986, respectively).

10. President's Blue Ribbon Commission on Defense Management, A Formula for Action: Report to the President on Defense Acquisition, April 1986.

11. The Affordable Acquisition Approach (A^3) Study, November 15, 1982, Air Force Systems Command, Andrews Air Force Base, MD.

12. Joint Program Study Final Report, July 27, 1984, prepared by the Joint Service Acquisition Program Management Study Ad Hoc Group. (Joint Logistics Commanders, Washington, DC).

13. Lanchester has stated that force effectiveness is proportional to weapons effectiveness, and proportional to the number of weapons squared. Thus, everything else equal, quantity may have a greater force effectiveness than quality.

14. J.S. Gansler and L.A. Kratz, "Effective Competition During Weapon System Acquisition" (monograph published by The National Contract Management Association), December 1985.

15. The higher range comes from both a GAO study of 1972 (Comptroller General of the United States, "Acquisition of Major Weapon Systems," DoD report B-163058, July 1972) and a 1979 report ("Inaccuracy of DoD Weapons Acquisition Cost Estimates," House Committee on Government Operations, November 16, 1979, Washington, DC); it was again reconfirmed as slightly over 2 to 1 in 1981 by the "Affordable Acquisition Approach," Air Force Systems Command, February 9, 1983. The lower range comes from attributing more of the cost growth to inflation effects.

16. Defense Science Board Summer Study Task Force, Department of Defense, Report on Use of Commercial Components in Military Equipment, 1986.

17. Motorola, Inc., Tempe, Arizona, December 1985 (data presented to the Packard Commission).

18. Importantly, this production savings can be realized even on relatively small quantity production lots, if the product is properly planned for manufacture in a factory that applies "flexible manufacturing" technology.

RISK REDUCTION COST AVOIDANCE FOR FULL SCALE DEVELOPMENT BEGINS WITH CONCEPT FORMULATION

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SUMMARY

This paper considers some critical areas that must be addressed in order to reduce the technical risk early enough in the Concept Formulation process to avoid undue costs during the Full Scale Development (FSD) program. Since the readers' view of Concept Formulation may vary substantially, the context here includes not only the definition of the traditional Required Operational Capability (ROC), Operational and Organizational Concepts, and the determination of the Best Technical Approach (BTA), but also a Preliminary Design Phase of the configuration(s) determined to be the BTA. Traditional cost drivers are first, requirements that may be more stringent than the minimum essential to perform the mission and secondly, design changes, after prototype fabrication, usually resulting in flight test delays, that stretch out the program. Design changes in the flight test phase are often made in a near panic environment, in order to minimize the schedule impact. Thus, they may not get the full scrutiny of producibility impacts, logistical supportability, and/or ease of maintenance considerations. The problems discussed are not meant to adversely reflect on anyone. They unfortunately tend to be typical even with a proactive government/industry development team effort. The need for an extensive and thorough Preliminary Design Phase as part of Concept Formulation will be apparent after reviewing the last series of major Army rotorcraft developments and explaining the problems encountered, together with the resulting solutions. Suggested work efforts to avoid these type problems in future developments are made to increase the potential of a new Weapons System "flying off the drawing board" within cost and on schedule.

MAJOR AIR VEHICLE DESIGN CHANGES IN FLIGHT TEST

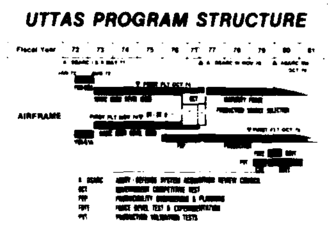

Figure 1

UH-60

First, I would like to cover the UH-60A (BLACK HAWK) Development. This was part of an overall Utility Tactical Transportability Aircraft System (UTTAS) program involving a "competi-tive fly-off" between two designs. The overall development spanned seven years and nine months (from award of FSD contract and approval to enter full rate production). The scheme of this development is shown in Figure 1. The Basic Engineering Development utilizes three prototype helicopters accumulating approximately 700 contractors flight test hours and approximately 750 government engineering and operational test hours. The government test effort included that required for the "fly-off" as well as the all important conventional airworthiness assessments.

This does not include a fourth company owned prototype which supplemented the government funded development program, but was fabricated relatively late during the first phase. A Ground Test Vehicle (GTV) was utilized for over 1200 hours of tie-down operation. During the maturity phase, an additional 600 hours of contractor flight testing was accumulated on the prototypes and 150 flight hours on the first two production aircraft. Government testing during this phase included another 150 flight hours utilizing prototypes and 1100 flights utilizing early production aircraft. GTV operations continued for another 700 test hours. The totals - 1450 hours contractor, 2000 hours government, and 1900 hours GTV.

One of the major design driver's in the UTTAS program was an unprecedented requirement for rapid air transportability. This requirement, as extracted from the UH-60A Prime Item Development Specification (PIDS) is as follows:

- 0 The actual loading or unloading time for one aircraft for C-141B air transport shall not exceed 30 minutes.

- 0 Maximum UH-60A air transport loading height for C-141B air transport, rolling and/or stowed, shall not exceed 105 inches, including pad. Top/sides minimum clearance for the UH-60A, in the air transportable configuration in C-141B transports, shall not be less than three inches.

0 Physical dimensions shall allow the aircraft with only rotor blades folded to be loaded into the C-5A air transport. Aircraft reassembly shall not exceed one hour.

These requirements drove the overall sizing of the UH-60A airframe and placement of the main rotor in proximity with the fuselage resulting in problems, the ultimate solution of which was raising the rotor mast which will be discussed later. The four bladed tail rotor is canted 20 degrees upward providing an element of vertical lift at the tail. This permits aircraft length to be minimized without severely compromising the allowable center of gravity range and resulted in a compact air trans portable design. The main and tail rotor blades as well as the tailcone are manually folded and the stabilator is removed prior to tailcone folding for air transportability. These requirements added weight and complex ity to the basic air vehicle as well as require the design and acquisition of an Air Transportability Kit to provide all common equipment required for preparation, loading, unloading and reassembly of the aircraft.

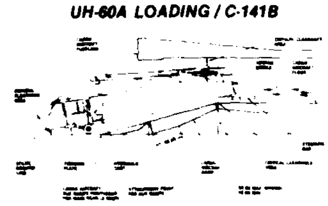

Figure 2

Placement of the main rotor in close proximity with the fuselage was a design decision mandated by air transportability requirements. The total height and width of the aircraft had to fit within a certain size envelope in order for the UH-60 to be air transportable in C-130 and C-141 aircraft. Flight tests produced unexpectedly high rotor system blade loads, fuselage vibration and interference drag. Based on the geometry consideration of Figure 3, Figure 4 (both from reference 1) shows the dramatic effect rotor height can have on blade local angle of attack by analysis. While Sikorsky diligently tried to maintain the original main rotor height by flight testing changes to the vibration absorber configuration and changes for drag reduction, it became apparent that the solution to the problem rested with raising the rotor mast to a level above the fuselage whereby the rotor to fuselage interference would be minimized. Sikorsky added a shaft extension which is removable so that the rotor can be lowered for air transportability. The decision to raise the height of the main rotor was implemented prior to the Government Competitive Test (GCT) and this arrangement remains unchanged to this day. This decision was based on data produced through exhaustive, extensive, and expensive trial and error flight test. Had the configuration decision on the necessity to raise the rotor been made based on data produced by a proper mix of analysis and wind-tunnel testing prior to flight, much effort would have been saved. A comprehensive concept formulation phase should include such a series of tests.

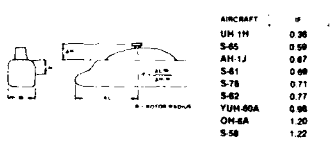

Figure 3

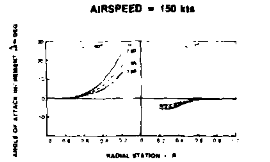

Figure 4

Sikorsky had originally intended to make the large stabilator on the UH-60A a fixed surface. Needless to say, the savings in weight and decreased system complexity were logical design goals for opting for a fixed versus a moveable system. Flight test showed that the fixed tail produced very poor pitch attitude during flares and low speed flight, extensive trim changes with changes in power, as well as performance losses due to down load on the stabilator due to main rotor wake impingement.

The Automatic Flight Control System (AFCS) was redesigned to allow for a moveable stabilator programmed to be 40 degrees trailing edge down from the horizontal in an approach to a hover and to move to a maximum of 10 degrees trailing edge up during high speed level flight. The stabilator system can operate in either the automatic or manual (emergency) mode. Stabilator positioning off-loads the stabilator since it is more parallel with the rotor wake during a flare. In addition, the programmed positioning of the stabilator improved aircraft pitch stability and the stabilator can be used to more effectively position the fuselage below the main rotor thereby reducing the control moment carried by the shaft and accruing the benefits of increased shaft fatigue life.

Figures 5 and 6 illustrate the impact of the movable stabilator on aircraft altitude and main rotor shaft loads.

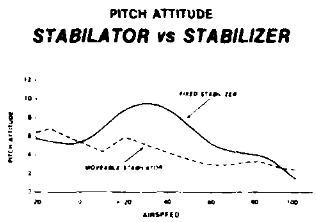

Figure 5

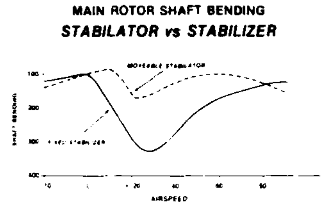

Figure 6

Flight test of the first design of the movable stabilator showed high blade passage frequency (4P) stabilator loads during moderate to high speed level flight. These loads were due to a combination of a stabilator reconance near 4P and stabilator excitation by vortex shedding by the blades as they passed over the nose position of the fuselage. The resulting stabilator motion contributed to cabin 4P roll vertical vibrations. Extensive ground shake tests and flight test produced a soft mounted stabilator which produced acceptable cabin vibrations and reduced stabilator loads. However, the aircraft still has a stabil-ator skin cracking problem due to the vortex shedding excitation. Each of the stabilizer/stabilator iterations were performed in hardware with extensive flight testings, ground testing, and schedule delays involved.

The Stability Augmentation System (SAS) is a dynamic rate stabilization system designed to provide rate damping of the helicopter. The original SAS incorporated an all hydraulic system composed of fluidic rate sensors, fluidic amplifiers and filters, servo valves and actuators.

The principal advantages of the fluidic SAS over comparable electronic mechanizations were considered to be inherent high reliability and reduced maintenance characteristics. However, changes in fluid viscosity with changes in temperature resulted in an inability to maintain constant flight control system characteristics. This was considered to be a deficiency which should be corrected prior to production.

The contractor had proposed several changes to the fluidic system for production to include larger flow paths both within the fluidic controller and in interconnecting actuators and manifolds for lower resistance to flow and better operation at low temperatures especially with higher viscosity MIL-H-83282 hydraulic fluid. Figure 7 illustrates the temperature effects. To further improve low temperature performance, state-of-the-art fluidic amplifiers were proposed. Other changes to reduce size and weight by eliminating prototype provisions such as extra bellows. extra amplifiers and manual bleeding screws were proposed. Modifications to the rate sensor and output circuit were also proposed to improve stability and handling qualities by reducing high frequency phase lag. These changes were also considered to provide improvements to the inflight response at lower frequencies. While all of these proposed changes may have resulted in improving the gain/temperature stability of the fluidic SAS over the full temperature range as well as eliminate some of the malfunctions experienced during the prototype development, the technology was considered to be high risk for production. The fluidic system was replaced by an analog and digital electronic SAS which is currently fielded.

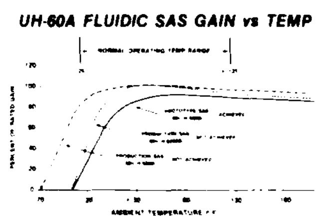

Figure 7

AH-64

Like the UH-60, AH-64 was part of "competitive fly-off", however the scope of the developmental effort prior to the fly-off was significantly less. It relates to what today will be considered a Demonstration Validation effort. The scheme of this development effort is shown in Figure 8. Phase 1, the developmental

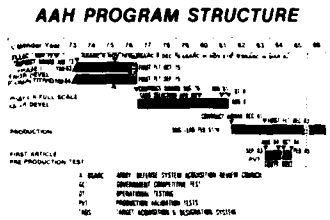

Figure 8

effort prior to the Government Comprehensive Test (GCT) was primarily air vehicle oriented. Weapons operation was limited to a rough cut assessment of structural implementation. Phase 1, utilized two prototype helicopters accumulating approximately 300 flight test hours and approximately 100 Government engineering flight test hours. The Government operational test effort was only 25 flight hours. A GTV was utilized for approximately 365 hours of tie down operation. During Phase 2, which constituted Full Scale Development (FSD) three additional prototype aircraft were manufactured. These were pri-marily for developmental and integration of mission equipment which incorporated a new Target Acquisition and Designation System (TADS)/Pilot Night Vision System (PNVS), a laser semi-active guided point target anti-armor missile (HELLFIRE) and a new 30mm area weapon. The contractors Phase 2 flight test effort encompassed an additional 980 hours of test-ing utilizing the two original prototypes and 715 hours of testing using the three new prototypes. The total Government testing, engineering and operational, on all prototypes during Phase 2 was 880 hours. This included 200 hours for Operational Test II (OT 2) which was the key prerequisite for a production decision. Continued GTV operation of over 1050 hours contributed significantly to the quality and reliability of the rotor-drive system. The loss of one test air-craft due to a mid-air collision, and early Phase 2 budget instability clearly impacted the overall schedule. The final qualification using early production aircraft included 170 contractor test hours and 140 Government test hours. The period between the initial contract award and the decision to enter production encompassed 8½ years. The totals are - 2175 hours contractor, 1145 hours government, and 1415 hours GTV.

The AH-64 went through a multitude of air vehicle configuration changes during its development phase. As the aircraft flight test envelope was expanded beyond 120 knots, several severe problems immediately surfaced; blade loads and fuselage vibration increased drastically with speed, the rotor flew too close to the fuselage, and the aircraft static stability, trimability, and pitch attitude, was inadequate.

A primary cause of the high blade loads at high speed was the inability of the blade trailing edge reflex to counter the cambered airfoil pitching moment characteristics at high Mach number (reference 2). This produced "Mach Tuck" (a very large nose down pitching moment) at Mach numbers above .86. Several potential solutions were unsuccessfully flight tested such as an extended trailing edge reflex in the tip region. Army experience with the swept-tip on the BLACK HAWK had proven that the swept-tip both reduced advancing blade effective Mach # and improved pitching moment charac teristics by moving the Aerodynamic center aft. The swept-tip was success fully grafted onto the AH-64 blade and flight test showed load reductions such as those shown in Figure 9 (reference 2).

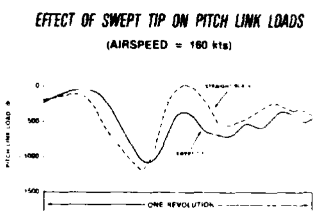

Figure 9

The first rotor height change on the AH-64 was primarily due to lack of clearance. Other benefits were decreased drag, increased performance, and reduced canopy drumming. Those benefits may or may not have been sufficient to have caused the rotor to be raised. The Army attributed the original clearance error to be due to incorrect blade flapping estimates, greater than expected deflections in the pylon support structure, greater than expected blade strap retention expansion, and improper droop stop design. The rotor was raised a second time to further increase canopy clearance. Of course, each time the rotor was raised, the support structure had to be redesigned and the rotor system tested to show that the proper whirl mode stability boundaries were met (reference 3).

The lack of static stability in the T-tail configuration was first attributed to poor air flow over the tail. Flight tests were conducted with numerous aerody-namic clean ups such as "turtle deck" strakes, removal of the black hole exten-sions, etc. There may have been aerodynamic solutions to the handling qualities problems, however, the T-tail configuration also produced high 4P Emphanage loads and high tail rotor loads at main rotor related 4P excitation frequencies. These

loads were due to main rotor wake excitations caused by to vortex shedding from blades passing over the tail boom. Numerous tip weight configurations were flown in order to "detune" the emphanage and reduce loads. The Army decided that the combined handling qualities/dynamics problems could not be solved (reference 4), and directed the contractor to go to a stabilator configuration. Of course, the first stabilator configuration had a fatigue problem due to the same wake excitation that effected the UH-60. A similar isolation fix was incorporated onto the AH-64. Many other minor aerodynamic changes were made to the AH-64 as a result of flight test. These include: elimination of the wing flaps (for reduced download) which were found to be not effective, the canopy went from flat glass to curved to reduce canopy drumming, the original long pylons which were supposed to reduce interference drag between the wings and the stores were shortened, and many aerodynamic fairings were added for drag reduction. Keep in mind all of these changes effected rotor and control system loads and aircraft stability so the "production configuration" was in a constant state of flux all through the development phase as engineering and management tried to guess whether proposed primary changes would produce higher or lower loads in other parts and more or less stability in the air vehicle, and perform concurrent redesign of the necessary parts. Since lead-times for new parts varied greatly with the manufacturing processes involved with making that part, the parts for the newest configuration did not appear on the flight line all at the same time. This further increased program risks as decisions had to be made based on flight test results from rapidly constructed configurations.

While the above mentioned development programs resulted in highly successful military aircraft meeting their full mission capability, the developmental task of achieving these aircraft could have been faster and less costly if basic configuration issues had been addressed through extensive wind tunnel testing prior to the launch of full scale development. These problems are essentially air vehicle configuration in nature; however, the potential for developmental delays in cost overruns is equally likely in other important areas of the weapon system. Mission equipment and man-machine interface are excellent cases in point.

The principle of a comprehensive engineering effort during Concept Formulation is not limited to airframe, aerodynamic/geometric type issues. It obviously applies to the use of simulators and must consider man machine interface issues. The very size and task of flight crew can be a major issue. Toward this end, the Army has recently completed an Advanced Rotocraft Technology Integration (ARTI) program.

Advanced Rotorcraft Technology Integration Program

The overall objective of the Advanced Rotorcraft Technology Integration Program was to pressure the contractor for the design of an integrated/automated cockpit which had potential for demonstrating single pilot capability and to reduce the risk of FSD. See Figure 10. A detailed analysis of the tasks associated with the various LHX missions was conducted to identify those points where high pilot workload was anticipated and to establish requirements for automation and/or realignment of effort to keep the workload within acceptable limits of a single crewman. Central to this task was the definition of workload assessment techniques which provided a basis for defining future simulation requirements and/or experimental flights to verify the workload estimates. The results indicated that with state-of-the-art automation concepts and proper consideration of man-machine interface control, the potential existed to achieve a single crew mission effective LHX system. Subsequently, a cockpit preliminary design and a supporting electronics architecture was established which would provide the proper levels of automation and assure that the crew station was configured to minimize the workload associated with completing the LHX missions. The Contractors finalized the design of the cockpit and supporting architectures by use of selected experimental flight tests and part-task simulations to verify that the automation concepts would achieve the desired workload reductions necessary to allow a feasible single seat design. Each contractor was provided a team of four Army pilots to conduct a wide array of design support tasks to include assessment of general cockpit arrangements and, in some instances, limited part task simulations of selected mission tasks.

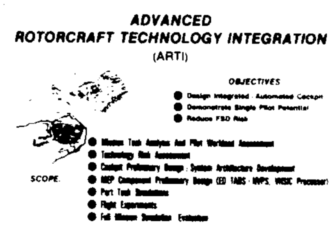

Figure 10

Approximately 375 hours of part-task simulations were combined with approximately 140 hours of flight experiments to support the overall design of the proposed LHX cockpits and supporting architectures. The part-task simulations included such minor issues as location of switches and displays to more complicated assessments such as the field-of-view requirements for adequate pilot vision during night, nap-of-the-earth flying. Additionally, considerable attention was directed at evaluating various configurations for flight controllers. Typical arrangements range from the conventional cyclic and collective sticks and tail rotor pedals to

a side arm controller which had all four axis controlled by a single lever. Part-task simulations were also used to evaluate a wide range of ergonomic issues to assure that the cockpit was configured in such a manner that maximum pilot effectiveness was maintained for the full range of basic pilotage as well as mission related functions.

Following construction of the final design cockpit, the Contractors conducted a full checkout to assure that the cockpit mounted in the Contractors simulation facility was capable of being operated for the full LHX mission scenario. The specific mission scenario used with the ARTI program was a composite of a full range of scout/attack mission requirements, and, in reality, was much more severe than any single mission anticipated for the LHX system. Such as approach was chosen to assure that the simulator would eventually overload the single crewman and, therefore, identify the high workload peaks for evaluation following the ARTI program.

Subsequent to the checkout of the proposed LHX cockpits, the Army's Simulation Evaluation Team (SET) visited each Contractor's facility for approximately 2 weeks. The first week was consumed with pilot checkout and simulator familiarization to assure that the Team was prepared to conduct the full LHX missions for official measurements. Many hours of simulations were conducted for measurements during the second week and provided a basis for evaluating the contractor's proposed cockpit design which would allow a single crewman to fulfill the LHX missions. The simulations not only assessed the potential of a single crew LHX helicopter system, but provided substantial amounts of information pertaining to the operational visibility of the LHX concept and a basis for the full scale development design. These simulations also provided an excellent insight into the issues associated with establishing rational and reasonable workload measurement criteria for use in the LHX FSD phase.

Almost 70 Government pilots conducted a total of 740 simulation hours and 140 experimental flight tests hours during the ARTI contracts. The experimental flight testing provided the Army with a wide range of evaluations that verified the proposed design concepts which will ultimately be used in the full scale development program. Additionally, these flight experiments provided valuable insight into the responsiveness of the various simulation concepts that strongly support the notion that heavy dependence on the use of simulators early in the LHX full scale development program is a viable approach for avoiding major problems in the overall development effort as well as minimizing the dependency on flight tests to assure an acceptable design.

The final results indicated that although potential for a single pilot exists, every aspect of the LHX mission could not be fully demonstrated during the ARTI contracts. Specifically, it is clear that a substantial improvement in simulator facilities will be necessary to fully evaluate the issues of air-to-ground targeting (including the implication of false alarms), night NOE pilotage (including a full consideration of restricted fields of view with FLIR imagery), and air-to-air combat (including the entire process of target acquisition, aircraft maneuvering for target engagement, and weapons operations). Figure 11 provides a summary of the contractor's and Government evaluation assessment of ARTI simulation results with regard to demonstration of single seat feasibility, and reflects the above comments. A separate user assessment of ARTI results is in Figure 12.

SINGLE CREW TECH FEASIBILITY

DEMONSTRATION STATUS

FUNCTION	INDUSTRY	GOVT	COMMENTS
FLIGHT CONTROL	1	2	Adv Flt Controls Significantly Reduce Workload
NAVIGATION	1	1	Integ GPS - Digital Map Automates This Task
COMMUNICATIONS	1	2	Capability To Automate & Simplify is Available
TARGETING	2	3	Need More Realistic Simulation of Alarms Targets
NIGHT PILOTAGE	2	3	Additional Simulation Required
AIR-TO-AIR	2	3	Additional / Higher Fidelity Simulations Required, Simulation Technology Issue

LEGEND: 1 – Feasibility Demonstrated With Confidence
2 – Feasibility Demonstrated With Moderate Confidence
3 – Further Effort Required

Figure 11

USER ASSESSMENT OF ARTI RESULTS

- BASIC TASKS (Aircraft Control, Navigation, Communication) CAN BE EFFECTIVELY ACCOMPLISHED WITHIN ACCEPTABLE WORKLOAD
- LOW FIDELITY OF NIGHT PILOTAGE, AUTOMATIC TARGETING AND AIR-TO-AIR SIMULATIONS PRECLUDE ADEQUATE ASSESSMENT OF RELATED WORKLOAD
- SOME MISSION TASKS MAY REQUIRE WORKLOAD REALLOCATION OR ENHANCED AUTOMATION
  - BATTLE COMMANDER
  - AIR-TO-AIR COMBAT
  - OFF-AXIS AIR-TO-GROUND TARGET ENGAGEMENT
- OPERATIONAL TESTING OF FULL PROTOTYPES IS REQUIRED BEFORE A SINGLE PILOT DECISION

Figure 12

Efforts to date since the completion of the initial ARTI contracts have identified those simulator upgrades which are essential to providing a full scale development facility capable of allowing early assessment of these three critical mission issues. The Army has also identified a full range of flight experiments that must be conducted in parallel with the early full scale development simulations to allow an early, high-confidence assessment of the LHX crew station design.

In summary, ARTI has provided the insight and specific data essential to defining and implementing a responsive simulation program for LHX in the area of design support, pilot training and support of development and operational testing. Additionally, a significant amount of simulation testing has already been completed which will ultimately become a part of the LHX total Development Test and Evaluation Program. Its overall contribution is outlined in Figure 13.

The use of simulators in the prelimi nary design process and to support full FSD is well known. It is not covered in this paper beyond the discussion of ARTI above because this symposium includes several papers dedicated to that subject. The engineering simulation tool is so powerful however that some firms simply take the approach of - make it fly to satisfy the pilots in the simulator, then have flight test match the simulator.

OVERALL CONTRIBUTIONS

- FIRST FOR ARMY AVIATION TO INVESTIGATE TOTAL MAN/MACHINE AND SYS INTEG PRIOR TO FORMAL INITIATION OF NEXT GENERATION ROTORCRAFT DEVEL
- CATALYST FOR HELICOPTER INDUSTRY INVESTMENT IN HIGH TECH SIMULATION FACILITIES TO ENHANCE DEVELOPMENT POSTURE
  - HELICOPTER CONTRACTORS HAVE MADE SIGNIFICANT STRIDES IN UNDERSTANDING SIMULATION REQUIREMENTS AS THEY APPLY TO MAN/MACHINE DESIGN ISSUES AS WELL AS AIRFRAME ISSUES
  - ADVANCED THE STATE-OF-THE-ART IN WORKLOAD ANALYSIS AS A DESIGN TOOL
- CONTRIBUTED TO ROTORCRAFT INDUSTRY'S DEVELOPMENT OF TOTAL SYSTEMS INTEGRATION OBJECTIVES
- FORMALIZED EARLY USER INVOLVEMENT IN SIGNIFICANT MAN MACHINE INTEG

Figure 13

Conclusion

Recent helicopter developments have resulted in a large number of significant design changes during the flight test phase. A thorough preliminary design phase, prior to initiation of FSD is the most appropriate way to minimize these changes. This effort must include extensive wind tunnel testing, component environmental investigations, and simulation efforts. The use of operational pilots during such simulations is highly productive. I am advised that the Boeing Company accomplished almost 10,000 hours of wind tunnel occupancy time prior to a fabrication go ahead on their Model 767 development and over 6,000 hours of tunnel occupancy time for the model 757. During the detailed design phase, a greater amount of wind tunnel testing was accomplished on each design. While wind tunnel testing of rotorcraft is not nearly as conclusive, the rotorcraft community can learn much from the traditional approach taken with fixed wing aircraft. The potential impact of unusual military requirements such as air transportability can be assessed before prototype fabrication begins. It is also essential to point out that much improvement is needed in the analytical prediction for rotorcraft. The key to reducing development cost and shorten the time frame rests with a concerted effort to enhance the possibility of the weapon system "flying right off of the drawing board".

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DEVELOPMENT SAVINGS THROUGH PARAMETRIC MODELING OF PROGRAM COSTS

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SUMMARY

Parametric modeling has been applied successfully to most facets of the weapon system preliminary design process. In the area of cost estimating, many parametric techniques are available to project production cost from system characteristics. However, development cost is usually estimated using grass roots techniques, a time-consuming and expensive approach. This paper proposes the application of parametric cost estimating to the derivation of development cost. Historical data from the individual contractor's experience is used as a basis for the model. Both system characteristics and program requirements are analyzed as potential cost drivers. Program alternatives can be evaluated based upon a quantitative assessment of financial risk, using equations sensitive to changes in requirements. The development cost model provides the opportunity to base decisions on sound information and to avoid the expensive iteration of grass roots estimating early in the concept formulation stage. The result is a significant savings in development cost.

1.0 INTRODUCTION

The development of major, new weapon systems demands early indications of program time and costs. The lead time required for budgetary estimates of future Government expenditures adds time and cost to the development program, and often locks the customer into system characteristics which can be developed and tested within predetermined schedule and cost boundaries.

Contractors have the responsibility to assist in providing early indications of risk associated with proposed system characteristics. In the past, response to mission requirements has been limited to a few configurations, with little variance in cost or schedule and limited identification of cost drivers. Much of the preliminary design phase has been dedicated to the iterative process of refining system characteristics and assessing their cost/schedule impact. This can be costly, time consuming, and especially frustrating if the discovery is made that proposed technical solutions require more time or money than has been planned.

Both Government and contractor teams need early modeling techniques which are sensitive to system definition alternatives in terms of cost and schedule impact. Computerized models could reduce development time and cost by shortening the iterative estimating process. This paper presents the proposal for a parametric model which predicts program time and costs from system characteristics, based on historical data. Possible system parameters are proposed, data base resources are identified, and methodology for model development is described. An assessment is made of the cost savings which could accrue to development programs which utilize such a model.

2.0 CURRENT METHOD OF DEVELOPMENT COST ESTIMATING

The grass roots method of development cost estimating usually involves collection of functional department inputs. The level of functional estimating varies from one contractor to another. In most cases, the following departments are involved:

- Engineering
- Manufacturing/Operations
- Materiel
- Logistics
- Program Management

Within each of these departments, detail estimates may be requested of subgroups. For example, individual design groups may be charged with estimating discrete design tasks. Manufacturing Engineering may be charged with estimating tooling costs, while Industrial Engineering is charged with estimating hardware fabrication labor hours.

At any one of these levels, techniques are applied based on the responder's experience. If parametric methods are applied, then they usually require a "low-level" type of input derived from fairly detailed job task descriptions.

The grass roots process can produce an accurate estimate. However, the process is time-consuming and expensive. Requirements for detailed job task descriptions seem frivolous, since the system requirements often change during preparation of the task descriptions. In addition, estimate sensitivity to cost drivers is difficult to measure.

An alternative to grass roots estimating, described in the following sections, is a parametric model which simulates the cost and schedule of a development effort based on system characteristics and program requirements.

3.0 PARAMETRIC MODELING

Parametric modeling is a technique which quantifies the relationship between a dependent variable (cost) and one or more independent variables. The process involves the following steps:

1. Collect and normalize cost data to the same economic base.
2. Investigate potential cost drivers.
3. Select independent variables from the potential cost drivers.
4. Develop relationships through regression analysis which predict cost using the independent variables.
5. Test the parametric relationships for validity.

During the past fifteen years, requirements for cost control have strengthened the cost engineering discipline. The idea of cost as a design parameter in weapon system development is firmly planted in the defense acquisition process. Parametric modeling has been applied most successfully to the prediction of unit production cost for hardware. Models have been developed to assist in setting Design-to-Cost (DTC) goals very early in the preliminary design stage of development. The same techniques can be applied to develop predictions of development cost and schedule.

The following sections detail the steps in the parametric modeling process as they relate to derivation of cost estimating relationships (CER) for development cost.

3.1 SOURCES FOR HISTORICAL COST DATA

The most available and reliable source of data for development costs exists within the experience of individual companies. Two types of data generally exist: actuals from previous development programs and cost proposals which did not mature into actual programs.

Actual development cost data is important to the analysis because it contains the impact of risks which may not have been originally predicted. These risks usually result in cost overruns. Actual data also offers visibility into cost drivers at least one level below the "confidence" level of the original estimate. For example, a contractor may have confidence in an estimate for engineering design effort, but not for specific subgroups within engineering.

Estimates for cost proposals are also an important source of data, since they represent the methodology which is used to make grass roots development cost estimates. An analysis of cost proposals forms the baseline in the model development, from which variations can be defined.

A third data source is the development cost of programs outside one's own company. Since cost data are proprietary, details are rarely available. However, total program costs are known through public information and can provide a means to establish upper and lower bounds for new program development cost estimates.

3.2 NORMALIZATION OF COST DATA

Historical program cost data should be normalized to a common economic basis. This is best accomplished by treating labor costs in terms of manhours and by adjusting material costs using a standard economic index.

Secondly, the data should be divided into major categories such as the following:

- Engineering Design
- Manufacture of Test Articles
- Test and Evaluation
- Logistics Support
- Other Program Costs

The remainder of this paper will focus on parametric modeling to predict engineering design manhours, although the same technique could be utilized in the other areas.

3.3 TYPES OF SYSTEM PARAMETERS

In developing a model to predict engineering effort, close examination of available cost drivers is imperative. Consideration must be given to potential independent variables which are known early in the preliminary design stage. Number of drawings, for example, may be a viable predictor of cost, but it is not quantifiable in the concept formulation stage. The following is a list of aircraft system characteristics and program-related descriptors which have potential as independent variables.

System Characteristics	Program Descriptors
Gross Weight	Single Contractor vs. Team
Empty Weight	Amount of Competition
Installed Power	New Development vs. Modification
Speed	Extent of Performance and Readiness Committments
Type of Aircraft	Schedule
Type of Flight Control System	Military vs. Commercial
Level of Mission Equipment	
Risk of New Technology	
Number of Configurations	

The suggested parameters provide guideposts in the search for cost predictors. For example, risk of new technology could be annotated to include dimensions for each of engineering (computer aided design), manufacturing (advanced composite hardware), and support (integrated checkout and diagnostic). Clearly, the presence of each requirement would impact development cost.

3.4 REGRESSION ANALYSIS

Multiple linear regression and correlation, and determination of the presence of multicollinearity are the statistical techniques used. Regression is a method used to determine a mathematical relationship between the independent variables (predictors) and the dependent variable (cost).

Correlation measures the closeness of the relationship. Multicollinearity, an undesirable condition, is present when two or more independent variables are highly correlated. This condition reduces the efficiency of the prediction for the regression parameters.

The following criteria are established to judge any equation produced using these statistical techniques.

1. Multiple correlation coefficient is greater than 90%.
2. Multicollinearity greater than the absolute value of 70% is eliminated.
3. Logical contribution of the variables is apparent.
4. Number of independent variables is consistent with sample size.
5. The resulting equation has good predictive capability.

4.0 POTENTIAL COST SAVINGS

The development of a cost model which is sensitive to variations in customer needs would be a valuable asset to engineering and program managers. The approach is straight forward. Implementation is the key.

High-level models are not sensitive to small changes in program scope. Models which require extensive inputs are not applicable in preliminary design. The technique described in this paper could be implemented to produce a model which represents the "middle ground".

Early indications of cost risk requirements could lead to an overall program savings of 10%. Cycles of detail estimating could be avoided if the customer has a clear and confident understanding of cost drivers. A development cost model not only identifies these drivers, but also quantifies their effects. Such a tool would be valuable to the customer as well as the development contractor.

PICKING WINNERS
PARAMETRIC COST ESTIMATING AND PROJECT MANAGEMENT

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Introduction

Project managers and development engineers might well be excused for thinking that they have more than enough cost estimates already. After all, the content of any major development programme is always broken down into numerous "work packages" and the costs of these individually estimated in fine detail. Then, as the work proceeds, these very detailed "bottom-up" estimates are continually refined and have a large claim on the attention of project managers.

However, it is the burden of this lecture that there is another form of cost estimating which can be used from the very inception of a project and which brings large returns from modest effort. Traditional methods assist attempts to control the costs of an on-going project towards some pre-set target. The methods described here are directed more at the initial selection of projects and the setting of feasible cost targets for them. In brief, their rôle is to pick winners from the range of competing alternatives which present themselves before a major project is begun. At the least, these methods give greater assurance that the chosen solution will be viable in terms of it being attempted within realistic cost constraints.

The penalties of mortality

The importance of embarking only upon viable projects is well illustrated by contrasting two hypothetical ,but representative, calculations.

First, Fig.1 shows a typical spend profile for development of a new aircraft and the results of either reducing the duration by one year or of halving the development cost of the engine (the effects of halving airframe or avionic development costs are similar). These are the types of change usually thought of in the context of reducing development time and cost. It would be a bold (or foolhardy) man who claimed any greater benefits for his next project as a result of any supposed advance in managerial or engineering technique.

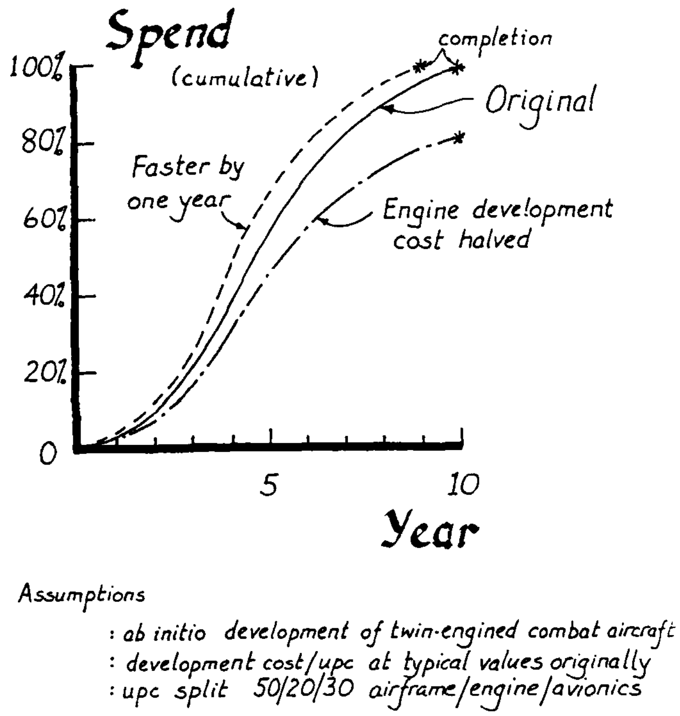


Fig. 1 : Possible targets for major improvements in a development programme

However, there is a major element of optimism implicit in presentations such as Fig.1 . They presume that the project proceeds to a successful conclusion. Unhappily, this is often not so. A proportion of projects are begun only to be cancelled later

-usually because their performance goals have been found to be incompatible with an acceptable cost. Work has to begin again in a fresh attempt to meet the military need.

Fig.2 results from applying this logic with typical mortality statistics [1] to the basic spend profile of Fig.1 . It thus shows the average (or most likely) build up of expenditure from the inception of work to it's final successful conclusion. Compared to the basic case of a single successful project, the expenditure is very similar in the common years ;but ,because of the possibility of false starts, the most likely expenditure continues to accumulate for some years thereafter.

It is evident that substantial savings would arise if it could be ensured that only viable projects were started. In both cost and time these exceed what may be hoped for from even t:~ most radical changes in project management.

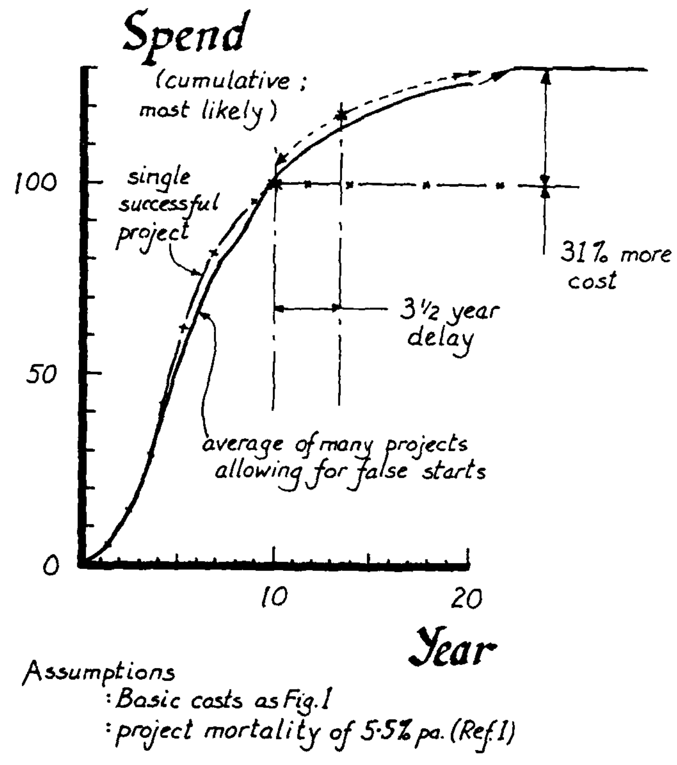
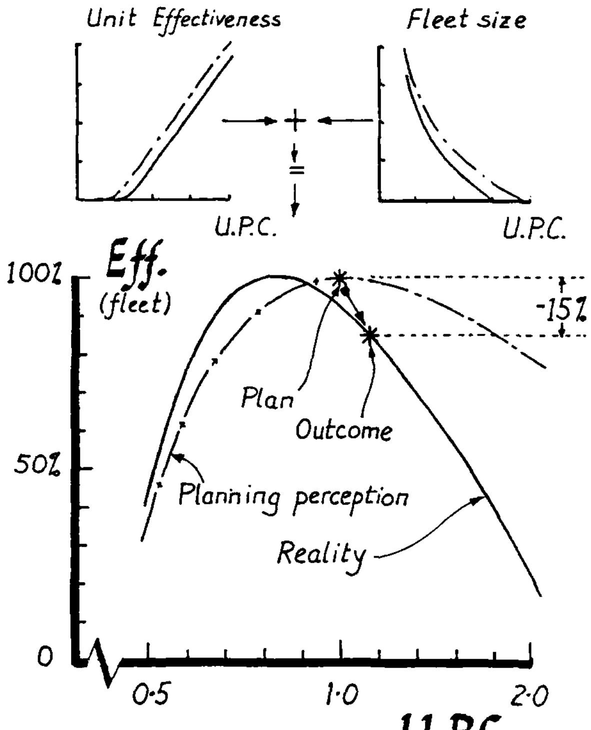


Fig.2: The costs of false starts

Missing the target

However incurred, cost increases that are not anticipated at the start of development must react adversely upon the cost/ effectiveness of a project. This is a large and difficult topic but the general principles must be as shown in Fig.3 . Cost escalation increases the unit cost of achieving any given unit effectiveness and ,both directly and by absorbing more money in development, this reduces the number of units that can be procured. Thereby, the design which was chosen because it was perceived as being optimum turns out not to be so and the fleet effectiveness is less than it might have been had accurate cost estimates been available as early as the concept-formulation stage.



Notes

: Fleet effectiveness normalised by maximum value

: Costs as Fig.1 : Theory of Ref.2 (perceived b=5½ l)

:"Plan for success" : Typical cost growth, fixed budget

Fig.3 : The price of optimism

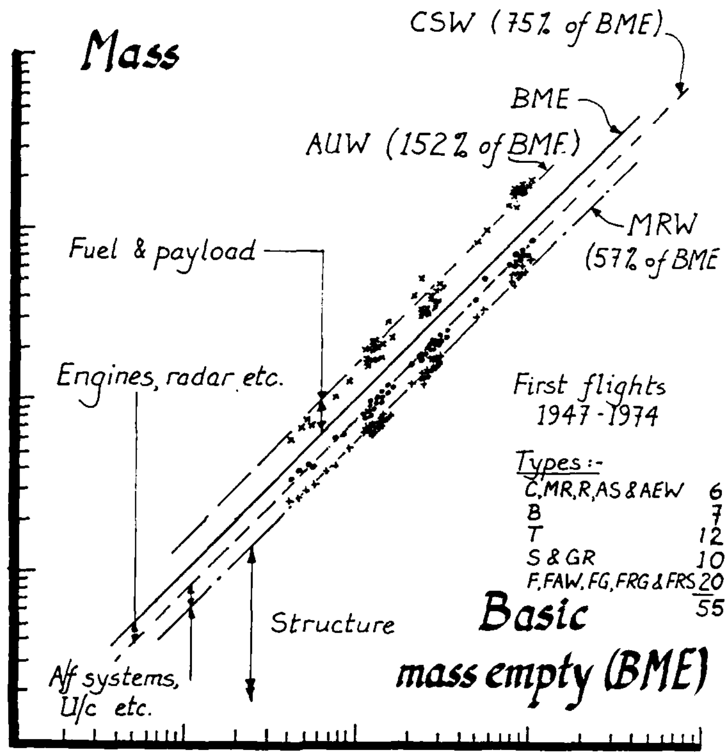


Fig. 4 : Plus ça change.....

Underlying consistencies

It is one thing to show the value of accurate cost estimates at the concept-formulation stage but quite another to provide them when they must rely upon the barest outline of a project -since that is all which will then be known. Such estimates have to depend upon the inter-relationships that must appear between the many detailed technical characteristics of each design -when fully worked out- if it is to be a rational example of it's type. Such relationships impose a high degree of consistency over a wide range of design solutions such as is illustrated by Fig.4 for the case of aircraft weight breakdowns. Even over quarter of a century, from cargo aircraft to fighters and for a 25 : 1 span of mass there exists a remarkable constancy in the division of weight between various functions.

Parametric estimates

The mutual dependencies between design variables means that ,despite them being very numerous, a few salient parameters can be used to characterise the whole. Indeed, as Fig.5 shows, the great majority of the costs of a wide range of military systems can be statistically associated with just three very basic characteristics -range weight and speed.

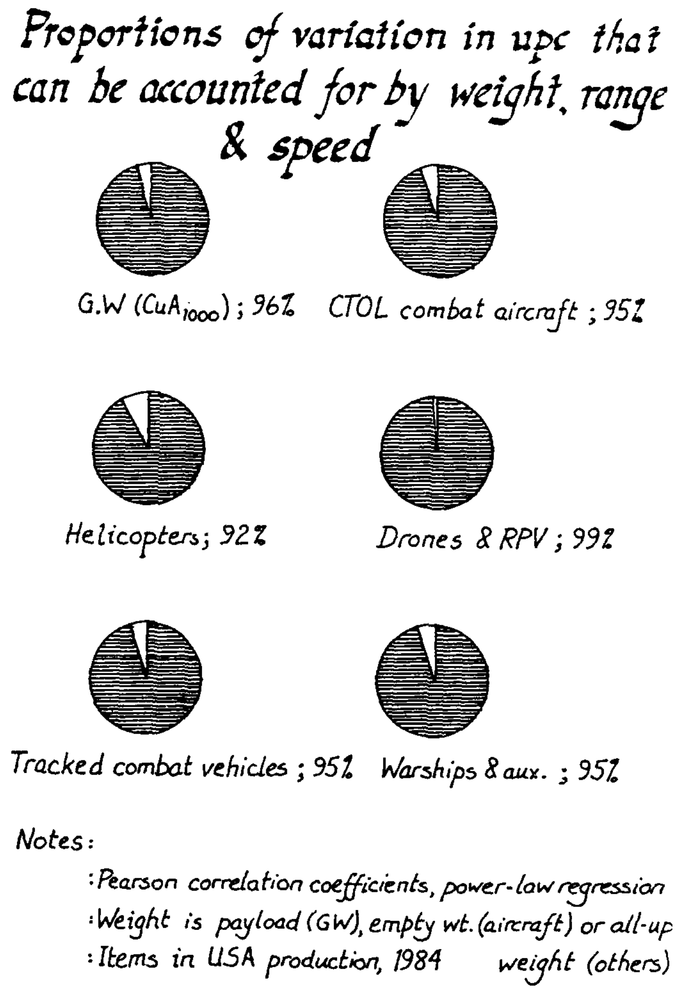
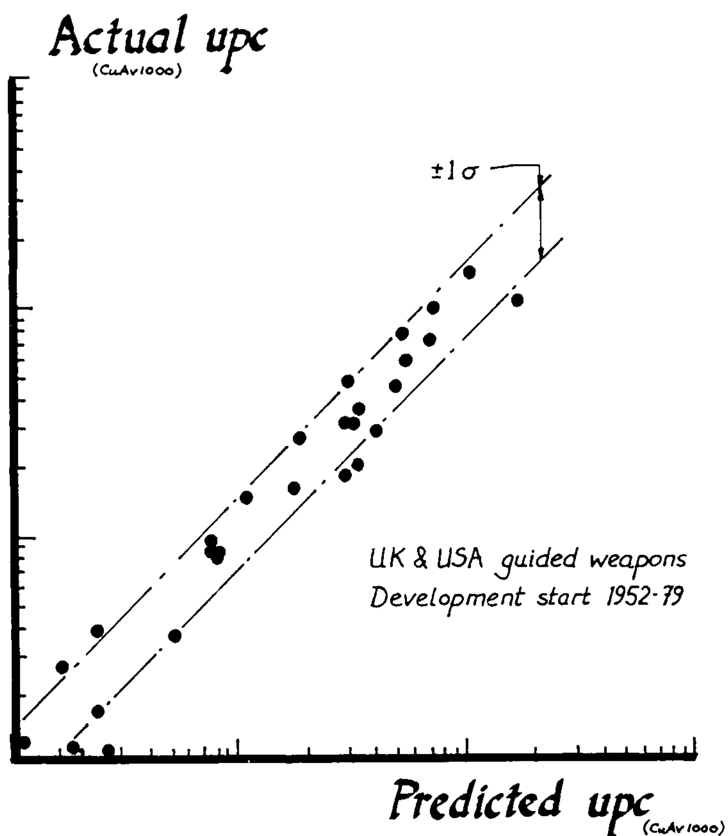


Fig.5 : Basics are nearly all

This ability to describe a project adequately in terms of only a few basic parameters enables so-called "parametric cost estimates" to be made before any design work has been done and when the barest outline of a specification comprises all the information available. For example Fig.6 demonstrates success in predicting the unit production costs of a wide range of guided weapons from just their maximum Mach numbers, ranges and warhead weights.



Predicted upc = Const x(Payload)^a x (Range)^b x (Mach No)^c

Fig.6 : GW cost and performance

When some sketch designs have been evolved then cost estimates can be based upon the salient characteristics thus derived. This is exemplified by Fig.7 which correlates aircraft production costs with empty weight and date -the latter acting as a surrogate for the technological standards of the industry. Despite it's simplicity, this approach is a powerful one. It can be extended [2 & 3] to deal with both modification programmes and with aircraft of other than the "latest and best" performance standards.

Correlations like these have a double message. On the one hand they show that it is possible to estimate costs from the earliest stages of a project. On the other hand, they show that it is essential to do so. Only then, will cost estimates be available to guide choice before values for the most basic parameters (that so largely determine cost) are finally settled upon and ,hence, while there is still freedom to reconcile these with the available budget.

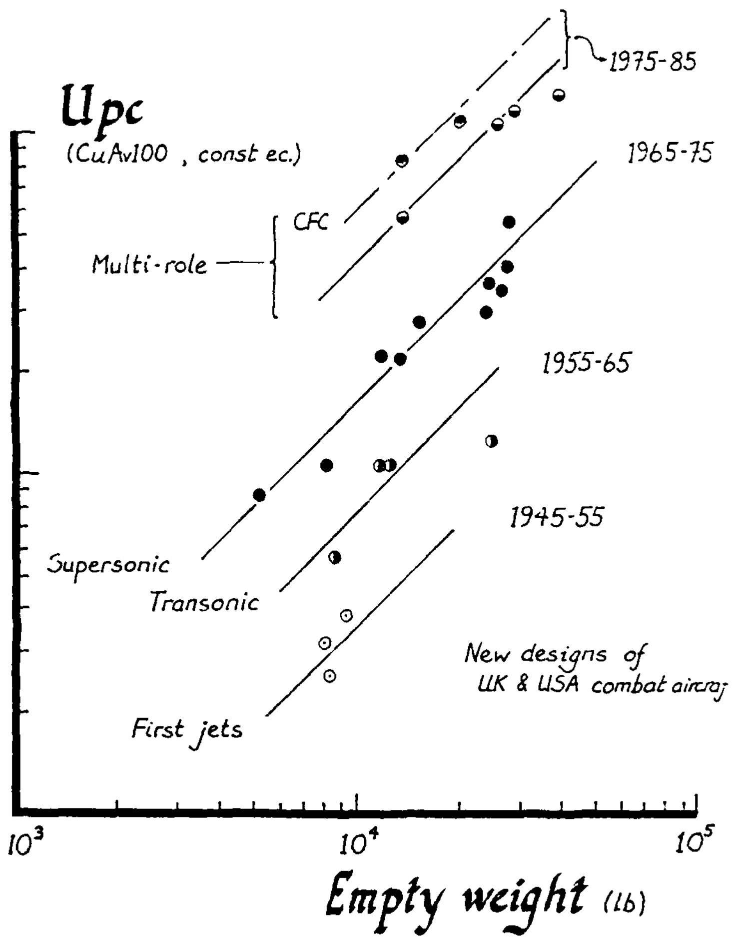


Fig.7 : Aircraft cost, weight & era

Nothing magic, nothing new

At this stage two points are worth emphasis. Firstly, this paper is not commending any of the various proprietory models which have been vigorously marketed in recent years. It is unfortunate that the term "parametric methods" has ,in some quarters, become mistakenly synonymous with such models since these commonly suffer from a rigid structure whose details are opaque. In contrast, what is advocated here is the construction of models by their users who embody their engineering experience in the qualitative form of the model which is then quantified by objective statistical analysis of data from past projects.

The second point is that there is neither anything magic nor much that is novel about such proceedures. The guise may be modern and the derivation more subtle mathematically but they are ,in essence, only a re-recognition of the value of very old practises. As long ago as 1665 the (English) Navy Board was explicitly using a formula involving keel length, beam and rate to price new warship construction, evaluate tenders and post-cost contracts. The competitive advertising of yards offering to construct clipper ships commonly offered prices on the basis of cost per unit cargo capacity according to insurance classification at Lloyds of London. In modern terms, these were "multi-variate, parametric cost-estimating relationships". The sole difference is that our forebears did not have so marked a penchant for multi-syllabic terminology.

Evolution not revolution

An objection sometimes raised to such traditional methods is that the pace of technical advance is said to invalidate reliance upon past experience. However, reflection shows that this cannot be so. Past experience also embodies (contemporary) technical change and ,so, is devalued only by a major discontinuity in design or production practise as when catching up with some ,hitherto neglected but now mature, advance in technology. That is most unlikely in the aerospace industry which prides itself upon being ever-alert to innovatations and ,so, embodies them as soon as practicable -often in anticipation of need.

Revolutionary change may be often predicted but it is rarely experienced. A good example is given in Fig.8 which contrasts contemporary predictions of the impact of introducing numerically controlled machining of integral aircraft structural details with

actual outcomes. There was a very definite effect but it took the progressive form of an amelioration of the rate of increase of cost rather than the sudden fall which had been predicted.

A pitfall ....

There is one way in which technical change can upset parametric cost-estimating methods -if used incorrectly. It is illustrated in Fig.9 which shows the results of setting up a parametric model (along the lines of Fig.6) using 9 early guided weapons and ,then, employing it to predict the costs of 19 other missiles presented to this fixed model in chronological order. The model behaves well initially but then fails quite abruptly with an increase in scatter, marked bias and a rapidly accumulating number of gross under-estimates. This failure is associated with the advent of cruise missiles.

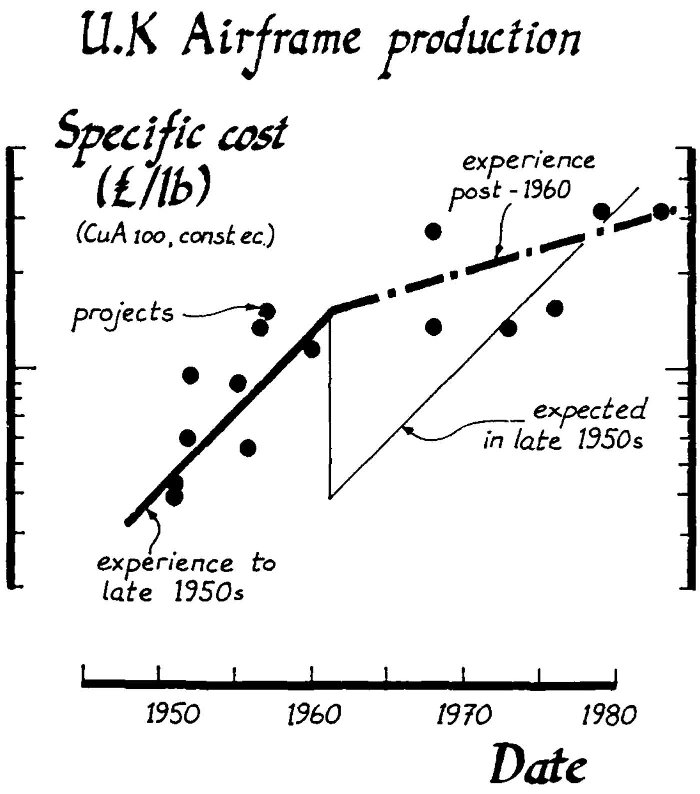
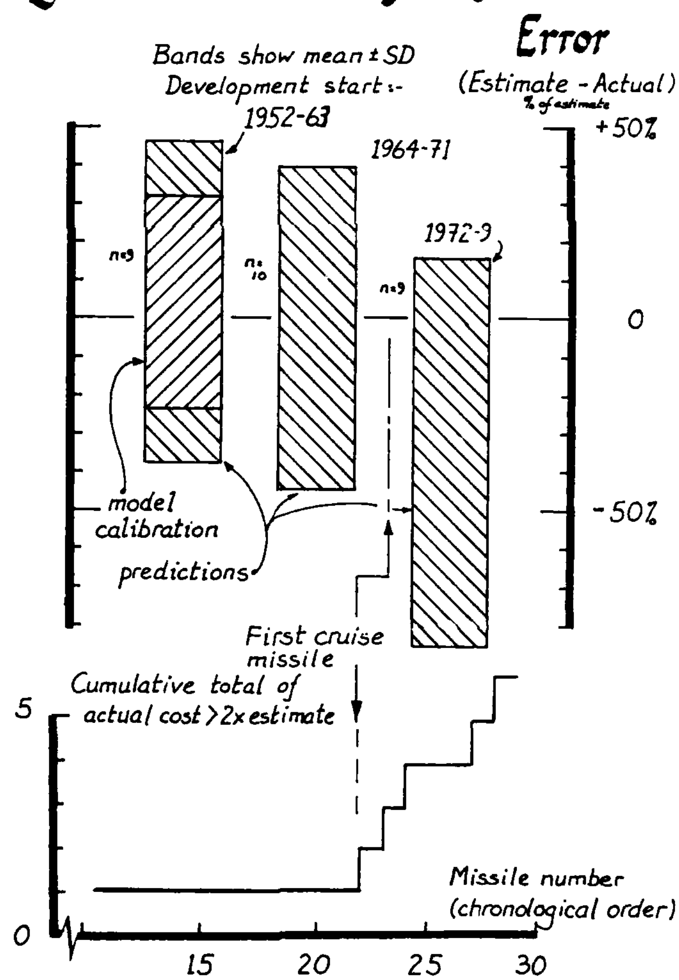


Fig.8 : Evolution not revolution

. . . it's detection . . . .

However, the reasons for this failure are discernable in the model's original calibration and ,so, trouble need not have come as a suprise. Examination of the statistical structure of the original model reveals ,as shown in Fig.10, that it's initial success was dependent upon correlations of payload and of range with Mach number. In other words, it was restricted to a particular design style which ,because of the limitations of contemporary technology, was the only one then current. Cruise missiles were a radical departure from that style.

Fig.9: New rôles defeat fixed model



The model failed not because of technical advances themselves but because several were combined to realise a whole new class of missile.

If ,as also illustrated in Fig.10, all missiles are included in the construction of an updated model then there is sufficient information for the analysis to disentangle the (previously intertwined) effects of Mach number and range. In consequence, the model is no longer vulnerable to such changes in design style.

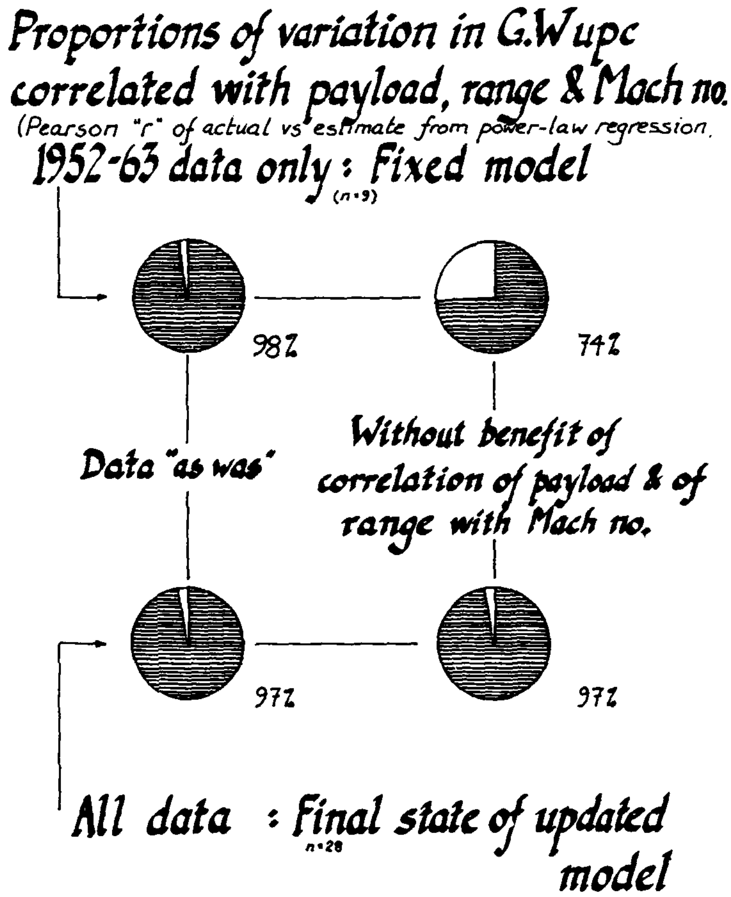
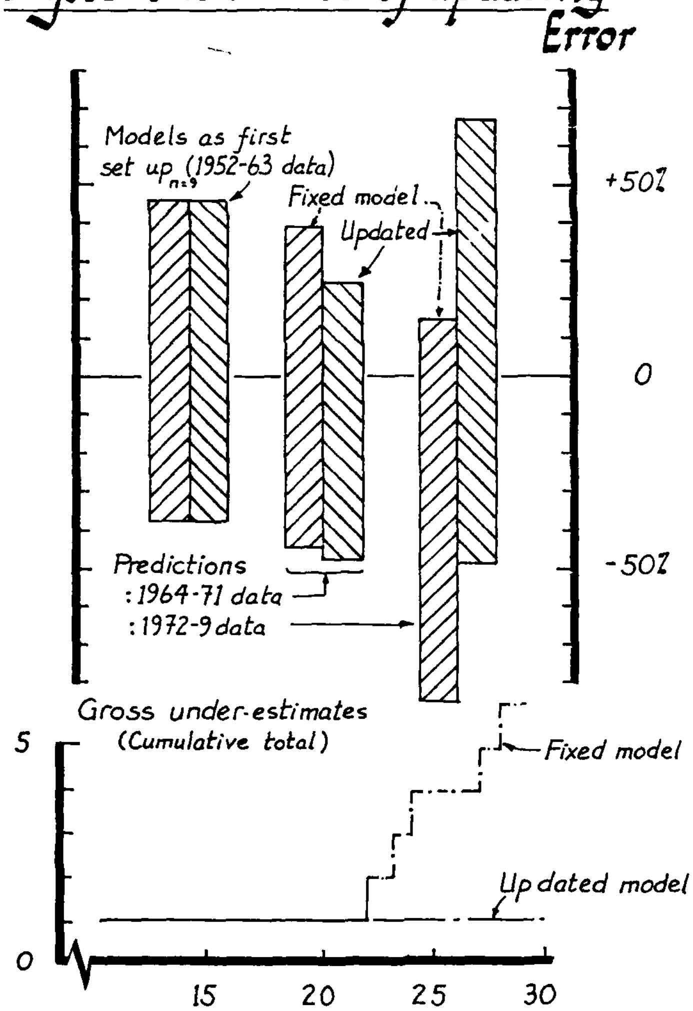


Fig. 10 : Hidden weakness

. . . . and aviodance

This demonstrates the necessity of continually updating cost-estimating models using all the information available. The efficacy of so doing is confirmed in Fig.11 which uses the format of Fig.10 to contrast the behaviour of fixed and continuously updated models. Updating aviods the appearance of bias and ,so, obviates almost all gross under-estimates. Consistent with earlier remarks on the prevalence of evolutionary -rather than revolutionary- change, the characteristics of cruise missiles were sufficiently foreshadowed in preceeding weapons for the analysis to recognise their possibility and to be prepared for it.

Fig.11: The merits of updating



To finer detail

Parametric cost-estimating is not confined to predicting global costs from a few characteristics of the complete vehicle. As a project proceeds, more detailed design data will become available. This enables parametric methods to be applied first to individual systems and ,later, to sub-systems and ,still later, to components. Thus "top-down" parametric estimates become progressively more detailed until they merge into the very detailed "bottom-up" estimates commonly used to control established production processes. Fig.12 suggests levels of entry to a typical cost structure appropriate to different stages of a project.

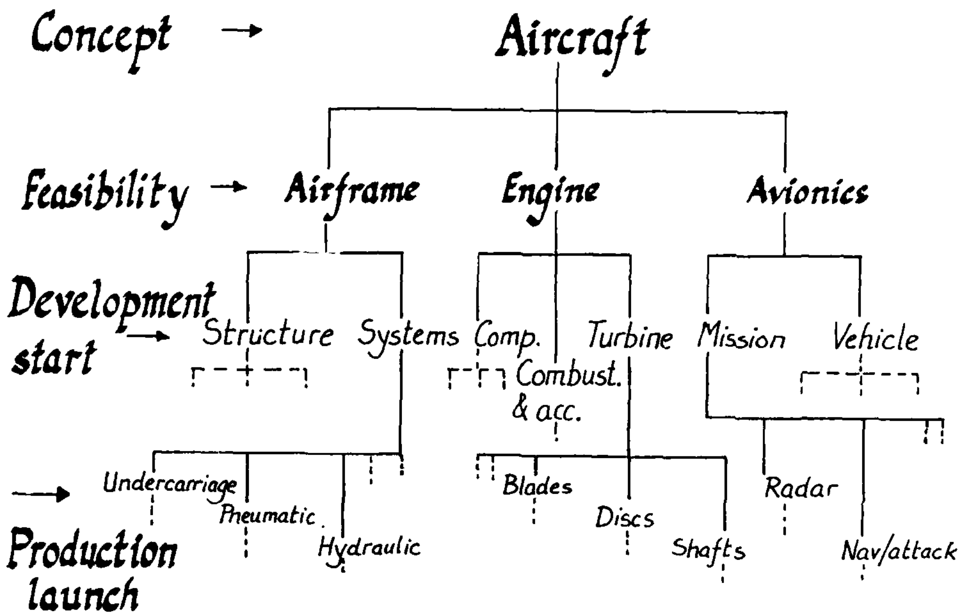


Fig.12: Entrances to a cost hierarchy

The need for contingencies

The availability of more data concerning a particular design enables estimates to be more specific to that design ;but it does not necessarily make them more accurate. Relating estimates closely to specific designs involves the implicit assumption that performance requirements will not undergo change and that the design (as proposed) will meet those requirements.

These are essential -albeit not popular- issues at the launch of full-scale development even though the customer will be convinced he has correctly specified his needs and the contractor will be equally sure that his design will meet them. Cost increases due to design and/or specification changes somehow manage to be both unexpected and yet usual.

It is salutary to remind ourselves ,as in Fig.13, of actual experience of cost over-runs relative to estimates made at commitment to full-scale development. These clearly show both a bias towards under-estimating and a wide spread of outcomes. It is proper to allow appropriate contingencies against both features [4] . The difficult problem is to quantify (and justify) contingencies appropriate to each particular project -every one of which ,it will be asserted, is better defined and less risky than the average.

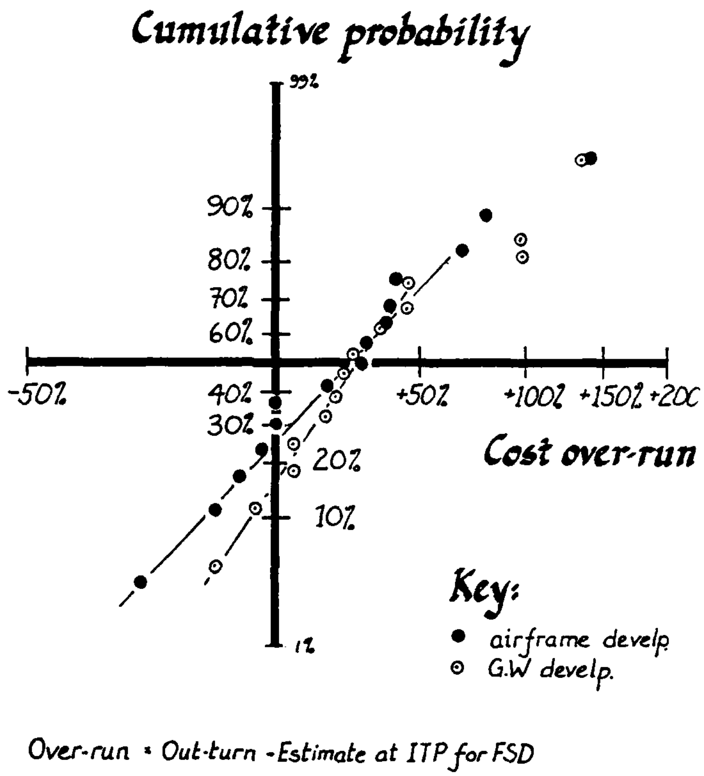


Fig. 13: Accuracy of cost estimates

Experience begets realism

A valuable corrective to the ,seemingly chronic, bias towards under-estimating cost is the performing of significant work before a final commitment to full-scale development. Fig.14 displays the correlation between expenditure in this preliminary phase and final cost over-run. Experience gained for the expenditure of about 10% of the full development cost removes systematic errors from the estimates.

These benefits in improved estimates and ,hence, better-informed decision making have long been recognised -as is manifest in the embodiment of formal Project Definition (PD) phases within the UK defence procurement cycle and in current support for technology demonstrator programmes.

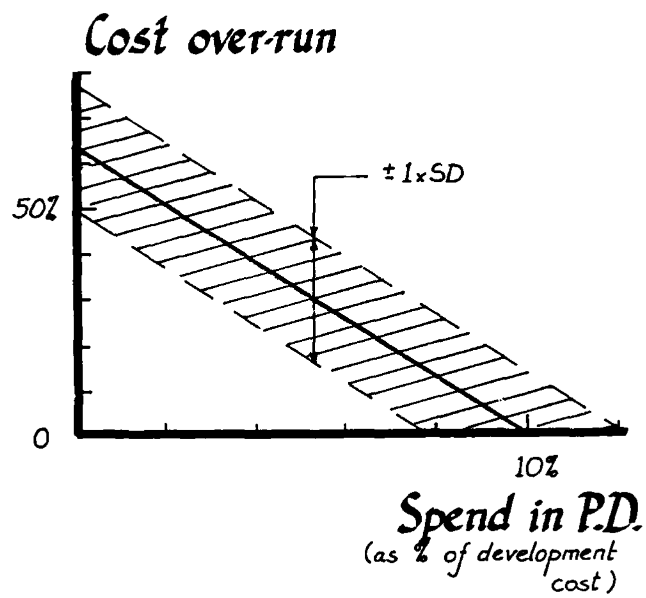


Fig.14 : Experience begets realism

Contingencies may have to recognise more than just the scope of work needed to meet the specification as then envisaged. Indeed, changes to the specification can often be a more important source of cost over-runs. Certainly, an analysis of aircraft projects whose results are shown in Fig.15, suggested that customer and contractor were about equally responsible for cost over-runs. Again, demonstrators and thorough PD studies can help by promoting realism in the matching of performance, cost and military needs.

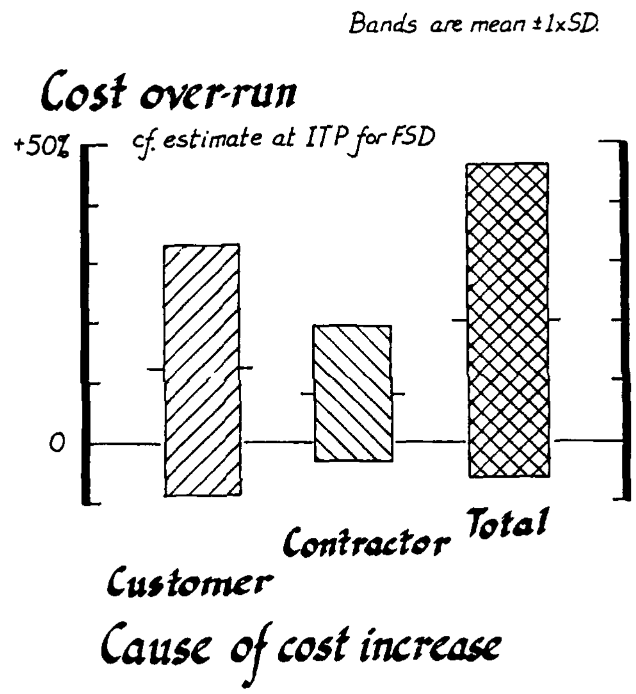


Fig.15: Who is to blame?

Uncertainty and risk

Turning to the spread of out-turns about estimates, any assessment of these must involve not just the inherent accuracy of the estimating methods but must also be concerned with the technical (and financial) risks to a project. Work towards quantifying these is still at an early stage ;but two approaches show promise. These are outlined in Fig.16 .

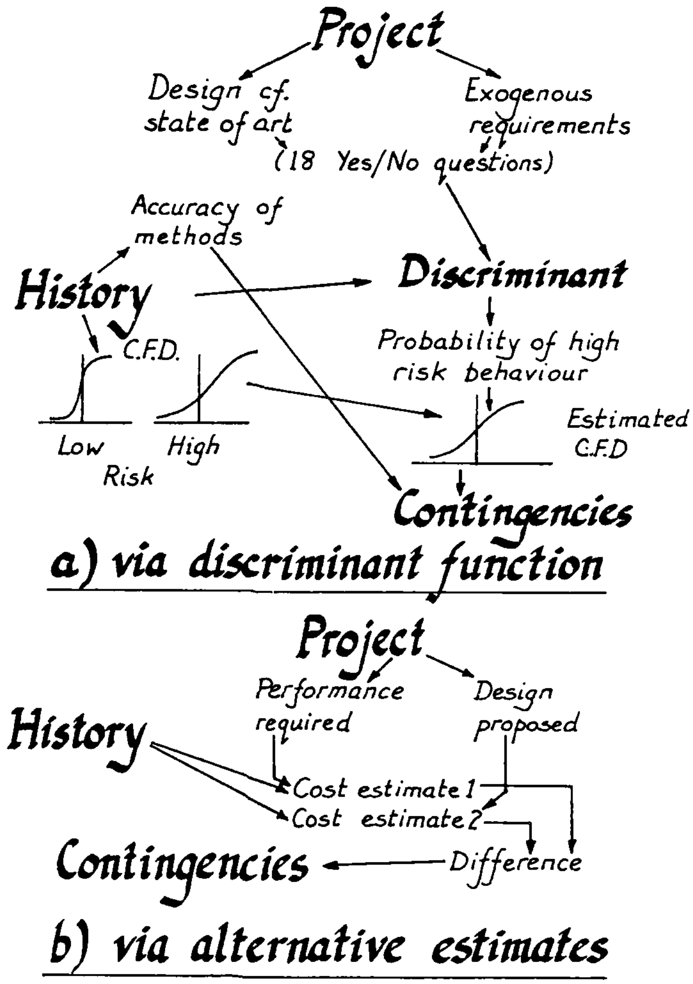


Fig. 16 : Quantifying risk

The first processes 18 (binary) characteristics of a project through a discriminant function which is statistically derived so as to optimise the classification of past projects into "high risk" and "low risk" categories. ("Risk here refers to the risk of the actual cost differing markedly from the estimate regardless of whether it is above or below the estimate). Examining a current project in the same way generates a probability of it behaving in a high risk fashion and ,so, enables a probability distribution of cost over- (or under-) run to be constructed. Appropriate contingencies can be chosen using this probability distribution.

The second approach is to form two independent cost estimates. One is based entirely upon the performance requirements while the other is based entirely upon characteristics of the proposed design. If these two estimates are in accord then all is well. Any substantial mismatch between the two estimates is a measure of the mismatch between design and requirements and of it's significance in cost terms. This then provides a guide to setting contingencies.

Understanding growth

All such relatively abstract statistical work must be underpinned by more detailed analysis to promote an understanding of what is going on in engineering terms. An example of this is presented in Fig.17 . It shows a correlation which supports the view that most of the growth of engine mass (during an aircraft development programme) is caused by demands to maintain overall thrust/weight ratio despite growth in the weights of airframe, avionics etc..

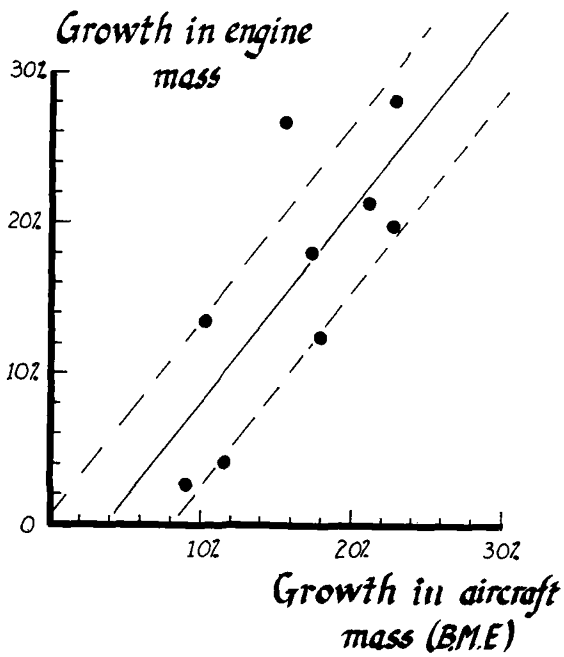


Fig. 17: Understanding weight growth

Summary and conclusions

Space has constrained this paper to a recital of salient points each supported by a single example. However, these suffice to demonstrate that parametric cost-estimating techniques are powerful tools most useful where they are needed most ie. in the earliest (and formative) stages of a project. In particular, when combined with systematic analysis of risk, they offer the best means oι "picking winners" from a pack of competing schemes. In this way, they can speed and cheapen development by obviating nugatory work on projects that turn out not to match early expectations of them.

Parametric cost estimating is not a set of commercial "black-box" opaque models with which the term has become unhappily confused of late. Rather, it is the application of statistical techniques to codify and quantify views of the world formed by engineering experience and commercial judgement.

Properly used, parametric cost estimating is a cutting tool of analysis and decision making. But, like all cutting tools, it has to be used with skill and care. If employed blindly or mechanisticaly then it becomes dangerous. In particular, it is essential that models are updated via their regular reconstitution using new data as they become available. Also, models must be open to review and informed criticism.

This is not to say that cost estimators ought to align themselves to every passing fashionable hope for cost reduction. On the contrary, they must cultivate respect for the integrity of historical data, an independence of outlook and a well-developed scepticism in the face of claims that "it will be better this time". Then, their advice can be unbiased and ,whether palatable or not, it should make a major contribution to the task of picking winners that must be at the heart of any rational procurement strategy.

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ETUDE PARAMETRIQUE DU COUT TOTAL DE LA MODERNISATION D'UN AERONEF EN FONCTION DU COUT DE DEVELOPPEMENT ET DE SERIE DES EQUIPEMENTS

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RESUME

Un aéronef fait généralement l'objet, une ou deux fois dans sa vie d'une "modernisation", afin de l'adapter à l'évolution de la technologie et du contexte de la menace, le plus souvent en améliorant son système d'armes et en le dotant de nouveaux capteurs. Une étude statistique a montré que le coût total d'un programme de "modernisation" était lié quasi-linéairement au coût de développement des équipements nouveaux et à leur coût de série.

De plus, les valeurs de certains ratios sont pratiquement constantes. Cette méthode globable permet d'apprécier intrinsèquement le degré de confiance de l'évaluation budgétaire du programme.

- CDEN : Coût de Développement des Equipements Nouveaux (développement et industrialisation
- CSEN : Coût de série des Equipements Nouveaux
- FF : Frais Fixes (coût total du développement et de l'industrialisation)
- PNS : Parties Nouvelles Série (coût des parties cellule, équipements, moteur ayant subi la modernisation)
- CT : Coût Total du programme de modernisation
- n : Nombre d'aéronefs à transformer

En raison de l'importance des coûts et des délais nécessaires au développement des matériels d'armement, en particulier dans le domaine aéronautique, les générations successives de matériels sont séparées par des intervalles assez longs, souvent supérieurs à une dizaine d'années. Comme, en outre, une fois le développement industriel d'un programme décidé, il est impensable que les armées ne passent pas commande du matériel concerné, et que toute modification, au cours du développement, des caractéristiques techniques est à la fois très difficile et très coûteuse à réaliser, on comprend que la décision de développer un matériel opérationnel entièrement nouveau soit prise avec le soin le plus extrême. Il est donc frequent qu'un matériel subisse, au moins une fois dans sa carrière, une "modernisation" afin de l'adapter aux évolutions techniques, et de le rendre capable de continuer à assurer soit ses missions opérationnelles, soit d'autres missions. C'est le cas pour les programmes français suivants, gérés par la Direction des Constructions Aéronautiques (DCAé) qui dépend du Ministère Français de la Défense.

Le bref descriptif ci-dessous indique l'objet principal de la "modernisation", le nom de l'avionneur responsable, le nombre d'aéronefs à transformer, et la date de mise en service opérationnel (effective ou prévue).

MIRAGE IV P (AMD.BA - 18 - 1986) : c'est une version modernisée du MIRAGE IV A, bombardier supersonique à long rayon d'action. La mission principale est la pénétration et l'attaque nucléaire tous temps avec le missile ASMP.

SARIGUE (DOUGLAS - 1 - 1976) : le SARIGUE (système aéroporté pour le recueil des informations de guerre électronique) est une version dérivée d'un DC 8 remotorisé, avion à long rayon d'action, permettant d'effectuer des missions de recueil d'informations.

GABRIEL (AEROSPATIALE - 2 - 1988) : c'est une version modernisée du N 2501 dont la mission est le recueil d'informations électromagnétiques.

ASTARTE (AEROSPATIALE - 4 - 1988) : l'ASTARTE (avion station relais de transmissions exceptionnelles) est une version dérivée du TRANSALL C 160, avion de transport militaire, pour l'emport de stations VLF durcies à l'impulsion électromagnétique.

GARDIAN (AMD.BA - 5 - 1983) : l'avion de base, le FALCON 200, a été doté de systèmes permettant d'assurer des missions de surveillance maritime.

MIRAGE 2000 N (AMD.BA - 112 - 1988) : c'est la version nucléaire du MIRAGE 2000 ; il a pour mission principale la pénétration tous temps à basse altitude avec le missile ASMP.

MIRAGE F1-CR (AMD.BA - 64 - 1981) : il est dérivé du MIRAGE F1 200, c'est un avion polyvalent, destiné à la reconnaissance, à la défense aérienne et à l'appui tactique.

ATLANTIC 2 (AMD.BA - 42 - 1989) : c'est une version modernisée de l'avion de reconnaissance et de lutte anti-sous marine, ATL 1, spécialement adaptée à l'emport et à l'exploitation des matériels électroniques et des armements pour la détection et l'attaque d'objectifs en haute mer.

SUPER ETENDARD (AMD.BA - 71 - 1977) : c'est la version améliorée de l'avion de combat marine Etendard IV M ; il s'agit d'un avion d'appui tactique embarqué.

Il s'agit donc de neuf programmes qui sont, soit terminés, soit à un stade très avancé de leur réalisation, et dont les données financières sont connues précisément. Les mathématiciens feront remarquer que le nombre de 9 constitue une base faible pour mener une étude statistique digne de ce nom. Cette remarque est certes fondée, mais il serait peu pragmatique d'attendre la fin du 21ème siècle à seule fin de réduire l'écart type. Il faut enfin préciser que, dans les programmes ci-dessus, il existe des programmes relatifs à la modernisation d'aéronefs existants, c'est à dire sans production d'avions supplémentaires (ex : MIRAGE IV P), et d'autres relatifs à la modernisation d'aéronefs dérivés, c'est à dire avec production d'avions supplémentaires (ex : MIRAGE 2000 N).

L'évaluation budgétaire du coût de transformation des aéronefs est généralement menée par le Directeur du programme concerné, suivant une approche analytique utilisant des statistiques et des comparaisons avec un aéronef aussi proche que possible de l'aéronef étudié (généralement l'aéronef dont il est dérivé, ou possédant un système d'armes comparable). La Direction des Constructions Aéronautiques a mené une étude afin de disposer d'une méthode globale permettant d'apprécier intrinsèquement le degré de confiance en cette évaluation budgétaire. A partir d'une analyse en composantes principales (réf. 1), elle a déterminé les variables liées, puis a abordé les méthodes explicatives (analyse canonique, régression) permettant de quantifier le degré de liaison. Il est ainsi apparu qu'on pouvait dégager deux variables explicatives :

CDEN : représente le coût de développement des équipements nouveaux à intégrer sur l'aéronef (frais de développement et d'industrialisation)

CSEN : représente le coût de série des équipements nouveaux

On peut alors étudier la valeur de certains ratios permettant de connaître le coût des frais fixes (F.F.), celui des parties nouvelles série (PNS), et le coût total du programme (CT), en n'incluant pas dans ce coût total les volants, rechanges et divers (VRD). On dresse le tableau de ces valeurs pour les neuf programmes (n représente le nombre d'aéronefs à moderniser).

	RATIOS	CDEN / FF	n x CSEN / PNS	n x CSEN / FF + PNS	n x CSEN / CT
AERONEFS EXISTANTS	MIRAGE IV P	54	54	21	21
	SARIGUE	55	65	45	45
	GABRIEL	52	44	18	18
AERONEFS DERIVES	ASTARTE	45	76	34	22
	GARDIAN	46	53	32	17
	MIRAGE 2000 N	58	81	39	20
	MIRAGE F1 CR	54	83	44	20
	ATL 2	55	78	41	29
	SUPER ETENDARD	56	77	44	32

On constate donc que, bien que ces programmes diffèrent assez sensiblement tant sur le porteur que sur la profondeur de la modernisation et le nombre d'aéronefs concernés, les ratios ci-dessus se situent dans des fourchettes, qui sans être très étroites, permettent de mener des estimations assez précises.

Quand, de plus, on se limite aux programmes présentant une grande analogie (MIRAGE 2000 N, MIRAGE F1 C, MIRAGE IV P, ATL 2, SUPER ETENDARD), la dispersion, comme la base statistique d'ailleurs, se réduit notablement. On a alors

RATIOS	Fourchette	Moyenne	Erreur maximale	Formule approchée
CDEN/FF	54 % - 58 %	56 %	± 2 %	FF = 1,78 CDEN
n CSEN/PNS	54 % - 83 %	68 %	± 15 %	PNS = 1,5 n CSEN
n CSEN/(FF + PNS)	21 % - 44 %	32 %	± 11 %	FF + PNS = 3,5 n CSEN
n CSEN/CT	20 % - 32 %	26 %	± 6 %	CT = 4 n CSEN

RELATIONS FF + PNS = a CDEN + b CSEN

L'analyse en composantes principales a permis de penser qu'une relation linéaire pouvait lier (FF + PNS) (c'est à dire le coût total du programme, en dehors de l'acquisition de nouveaux appareils) aux deux variables explicatives CDEN et CSEN. Deux approches mathématiques sont possibles (méthode des moindres carrés) :

- l'une à partir des valeurs absolues, c'est à dire en cherchant une relation :

  FF + PNS = a CDEN + b n CSEN

- l'autre à partir des valeurs relatives, c'est à dire en cherchant une relation :

$$1 = a \frac{\text{CDEN}}{\text{FF + PNS}} + b \frac{\text{n CSEN}}{\text{FF + PNS}}$$

Bien que cela ne soit pas évident à première vue, on n'obtient pas les mêmes valeurs des couples (a, b) suivant l'approche faite. Le calcul effectué à partir des neuf programmes donne :

1ère méthode : FF + PNS = 1,862 CDEN + 1,225 n CSEN
2ème méthode : FF + PNS = 2,244 CDEN + 1,1811 CSEN

Le tableau ci-dessous compare les valeurs réelles aux valeurs calculées à partir des relations ci-dessus.

Ecart R/Calc *	FF + PNS 1ère méthode a : 1,862 b : 1,225	FF + PNS 2ème méthode a : 2,244 b : 1,181
ATL 2	+ 1 %	- 7 %
MIRAGE 2000 N	- 4 %	- 14 %
SUPER ETENDARD	+ 2 %	- 5 %
MIRAGE F1 CR	- 1 %	- 9 %
ASTARTE	+ 12 %	+ 4 %
MIRAGE IV P	+ 12 %	0 %
GABRIEL	+ 20 %	+ 10 %
SARIGUE	+ 13 %	+ 9 %
GARDIAN	+ 27 %	+ 22 %

* Lorsque l'écart est négatif, la formule conduit à une valeur plus élevée que la valeur réelle.

La première méthode conduit à une relation qui est satisfaisante pour les gros programmes, ce qui est normal puisque ce sont les valeurs absolues qui servent aux calculs. De ce fait, elle sous-estime systématiquement les programmes moins importants.

La deuxième méthode, qui utilise les valeurs relatives, conduit à une relation satisfaisante pour des programmes de moyenne importance.

Dans le cadre d'une évaluation budgétaire, il faut appliquer, pour les programmes moins importants ($<$ 2000 MF) la deuxième relation et majorer le résultat d'environ 10 %. Pour les gros programmes, la première relation semble plus précise.

Les ratios ou relations précédentes s'appuient essentiellement sur les valeurs de CDEN et CSEN (on suppose que le nombre d'aéronefs à transformer, n est connu précisément). Une étude a montré que ces valeurs peuvent évoluer pendant la vie d'un programme, il convient donc d'être prudent et se souvenir que l'objectif premier de la méthode ci-dessus est de vérifier que les ratios et coûts totaux se situent bien à l'intérieur des fourchettes définies. La prévision budgétaire est possible, mais devra être recoupée par les méthodes analytiques.

En conclusion, l'étude menée par la DCAé n'est qu'une pierre dans l'édifice de la connaissance des coûts de programme ; elle a permis de définir deux ratios relativement significatifs : CDEN/FF et n CSEN/PNS, et une relation liant linéairement (FF + PNS) à CDEN et n CSEN. Malgré une base statistique restreinte (9 programmes), son application à de nouveaux programmes (modernisation du SUPER ETENDARD par exemple) a conduit à des résultats intéressants.

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THE INCREASED TIME AND COST OF DEVELOPMENT: CAUSES AND (SOME) REMEDIES

by

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SUMMARY

This paper contains a discussion of the increased time and cost of development required for air vehicles. Concurrently, methods of reducing time and cost are examined. The evolution of air vehicle development is presented to provide the background surrounding technological advances. The increased time and cost associated with those advances are discussed in relation to methods of gaining time and cost reductions.

In the last forty years, new military fighter aircraft have grown increasingly more sophisticated in response to new or anticipated enemy threats. Growth in aircraft capability has coincided with advancements in technologies, including propulsion, aerodynamic design, control systems, structural materials, and avionics. The greater complexity in the aircraft involved in full-scale engineering programs has complicated the design analysis and test processes. A full-scale development program, as a precursor to production, must not only evolve a design which meets the defined performance requirements, but one which is capable of being produced at acceptable cost using established production processes.

Recognition of the increasing burden of operating and support costs for military aircraft has resulted in a concentration of focus on requirements for supportability in the aircraft design. This is reflected in stringent reliability and maintainability requirements. The high cost of today's aircraft has caused the imposition of longer service life requirements with a resultant emphasis on structural integrity and fatigue life. The effect of these new thrusts on the development process is to complicate the design, analytical, and test processes.

The higher level of requirements, the need for establishing a design which balances competing requirements of performance, structural integrity, supportability, cost, and weight, and compliance with customer tracking and reporting requirements, have resulted in a steady increase in the number and size of tasks which must be accomplished during a full-scale development program. Although this appears to be an irreversible trend, there are specific approaches and techniques which can be used to increase the effectiveness and efficiency of the airframe contractors' development efforts to ensure that the cost and time duration of development programs are controlled.

HISTORICAL PERSPECTIVE

Since the end of World War II, the complexity of military aircraft designs has been increasing. In the wartime situation, large quantities of relatively unsophisticated aircraft were required. Long-term service life was not a distinct design requirement. In the peacetime environment, the long-term strategy is the development of systems with capability required to meet the potential threat in the event of hostilities. As the level of sophistication of the threat increases, the demand for increased capability in defense systems increases as well.

As the complexity of aircraft has increased, so has the unit cost. The economic necessity of preserving assets has resulted in the development of redundant systems for survivability, passive and active defensive avionics, low observables technology, and protective systems to minimize vulnerable areas. All these things add to the design requirements which must be met during development and to the cost of the end product, eventually turning it into a high-cost, non-expendable weapons platform. Figure 1 shows the progression of fighter aircraft flyaway cost over the last four decades and projections for the future.

As the complexity and cost of aircraft increase and the development times stretch out, there is a natural reduction in the number of new program starts and an attendant increase in the necessary planned economic life for the aircraft. Figure 2 shows the trend in reduction in the number of fighter aircraft types and quantities procured by the U.S. Air Force since World War II. It appears that the ATF will be the only major USAF fighter development in the 1980s and 1990s.

Prior to 1960, there were no specific fatigue life design or test requirements in fighter aircraft design. In the late 1950s, the first formal structural service life requirements were imposed for the T-38 supersonic trainer. For early fighter aircraft, designed to meet static loading requirements, the fatigue life was not established, but was probably 2,000 to 3,000 hours. Modern fighter aircraft fatigue requirements are now 6,000 to 8,000 hours with much more severe loading spectra than earlier aircraft.

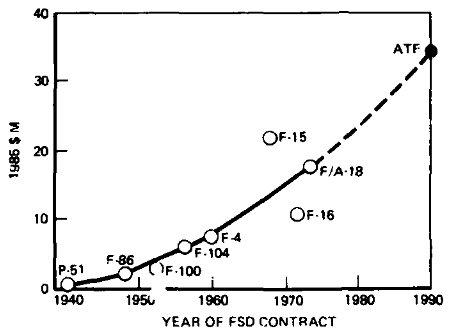

FIGURE 1. RECURRING FLYAWAY COST OF FIGHTER AIRCRAFT

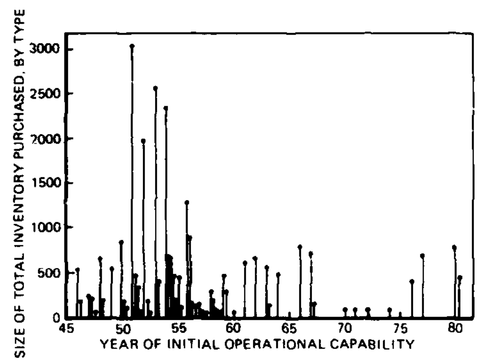

FIGURE 2. MAJOR MODEL VARIANTS OF USAF FIGHTERS AND QUANTITIES PURCHASED, 1945-1980

Figure 3 shows the increase in fatigue life with time for several aircraft development contracts in the time since 1962.

The increased requirements for aerodynamic maneuverability, weapon delivery, and various forms of offensive and defensive avionics have caused growth in on-board equipment weight and, consequently, the size of the aircraft required to carry this equipment. Figure 4 shows the increase in aircraft equipment weight with time. The F-16 and F/A-18 were derivatives of the USAF Lightweight Fighter competition and therefore show a departure from the large fighter trend reflected by the F-14 and F-15.

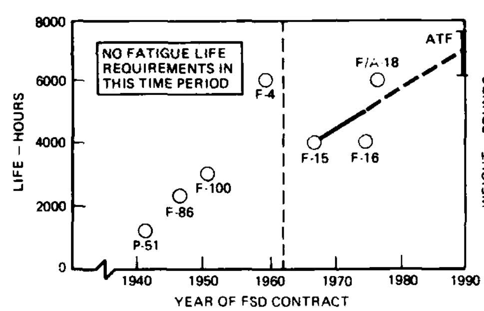

FIGURE 3. FIGHTER AIRCRAFT FATIGUE LIFE REQUIREMENTS

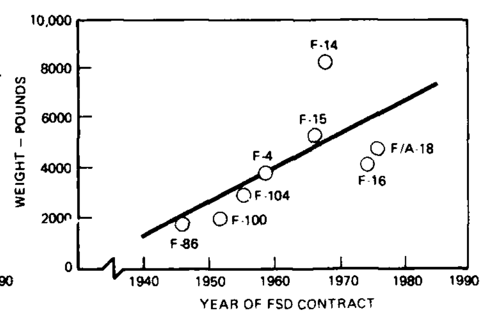

FIGURE 4. GROWTH IN FIGHTER EQUIPMENT WEIGHT

A major portion of the equipment growth has been in flight controls, avionics, and on-board computers. The increased demands for maneuverability have caused the development of increasingly complex electronic flight control systems. Over the last 15 years, there has been a corresponding growth as well in integrated electronic control of weapon delivery systems, communications, navigation, and propulsion systems. The transition from vacuum tube electronics to solid-state and later to integrated circuits, large-scale integration (LSI), and now very high speed integrated circuits (VHSIC) has permitted dramatic reductions in size and weight required to perform specific electronic functions. Yet the total weight of avionics in modern aircraft continues to increase with the addition of new capabilities and complexity, more than offsetting the potential of weight reduction afforded by electronics technology.

The development of high-speed digital computers over the past 15 or 20 years has permitted modern-day fighter weapons systems to include previously unheard of computational power, which has permitted centralized computer control of the entire range of aircraft electronic systems. This technology has permitted the development of quadruplex fly-by-wire flight control systems, digital graphic instrumentation displays, multimode radar systems, and highly sophisticated augmentation for flight and navigation.

All these things add enormously to the pilot's capability, but also to the cost of development for this on-board equipment. Software development to support the on-board computer equipment is now a major task in full-scale development.

The using military customer has recognized that in a peacetime environment the main operational economic factors are the availability of aircraft for use when needed for training and readiness, and the recurring support costs in the form of spare parts and equipment, maintenance personnel, and test equipment. This has resulted in a major thrust to formalize the imposition of stringent reliability and maintainability design requirements to ensure that airplanes developed for military use will not only perform in accordance with established requirements, but are developed using design principles that result in: (1) adequate levels of reliability to control in-service failure rates; and (2) maintenance characteristics that permit economic servicing with realistic levels of maintenance capability and logistics support resources. Figures 5 and 6 show the trends in aircraft reliability and maintainability.

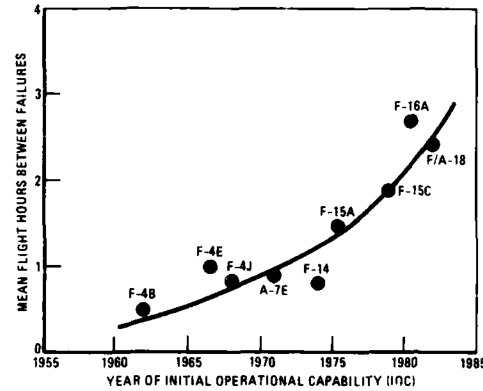

FIGURE 5. INCREASING AIRCRAFT RELIABILITY TREND

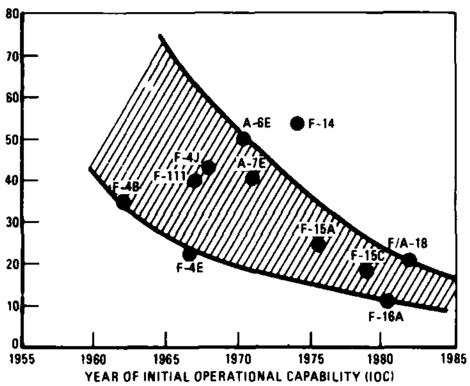

FIGURE 6. DECREASING AIRCRAFT MAINTENANCE REQUIREMENTS

The result of these increasing complexities in the development process has caused concerns in both government and industry about the trend toward lengthening development times and the related increase in cost. As well, the potential for obsolescence at the time of deployment for systems which require more than five years to establish initial operational capability is an additional concern.

One of the concerns in the issue of cost of full-scale development programs is the implication of cost growth and overruns associated with these types of programs. This has been the subject of Congressional controversy and has been widely covered in the public press. In actual fact, cost growth has been declining in recent years. Figure 7 shows cost growth for programs in the 1960s, 1970s and 1980s. The program average bars are unadjusted cost growth percentages, whereas the dollar weighted bars are adjusted to give proportionately heavier weighting to more costly programs.

As can be seen, cost growth in major weapon systems acquisition programs has decreased progressively on a percentage basis and has decreased even more rapidly for higher dollar value programs. This reduction in growth may result from a variety of influences, including the use of more realistic cost estimates for FSD, improved cost estimating techniques, and an increasing tendency to strive to avoid program cost growth by allowing some contingency margin in estimates. It is also likely that real cost growth reductions may have resulted from improved development strategy and program cost controls. An additional factor limiting cost growth in FSD is the tendency in recent programs deliberately to control development program cost by limiting the degrees of technology development in FSD and providing for preplanned production improvement (P^3I) in production to allow for the increasingly severe budgetary restraints on new programs.

DEVELOPMENT PROGRAM EFFECTS

The specific effects of added systems complexity on development program duration and cost are extremely varied; however, they can be characterized in a few specific categories.

Advancements in technology carry uncertainties which always accompany pushing state-of-the-art boundaries. The approach which must be taken to control risk in advanced technology development programs generally results in a more costly development process, often requiring the pursuit of parallel paths or the development of contingency alternatives, which add both cost and time to the process compared to the implementation of proven technology.

Increased system complexity adds to the time required and costs associated with all facets of the development process, including design, analysis, simulation and test, as well as tooling development and manufacturing.

Since full-scale development (FSD) leads into the production program, a further requirement of the engineering development process is to define a design (product) which can be reasonably and repeatedly manufactured using established and controlled manufacturing processes. Haste in engineering development and failure to ensure the producibility of the design in a production environment have been the cause of problems in many military production programs.

A prudent development program which minimizes production risk must avoid excessive concurrency (development and production) to ensure that problems identified during development can be resolved and corrected before the manufacture of significant numbers of production aircraft. This consideration is the major factor in delay of the design freeze point (the physical configuration audit airplane) to minimize the economic consequences of retrofit or corrective changes in aircraft after delivery. Figure 8 shows the lengthening trend in the span of time from FSD start to first flight to first production delivery.

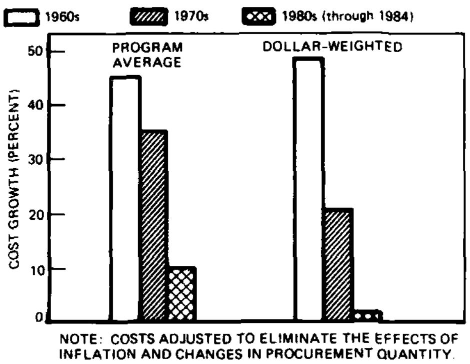

FIGURE 7. COST GROWTH FOR PROGRAMS AT THE END OF THE 1960s, 1970s, AND 1984

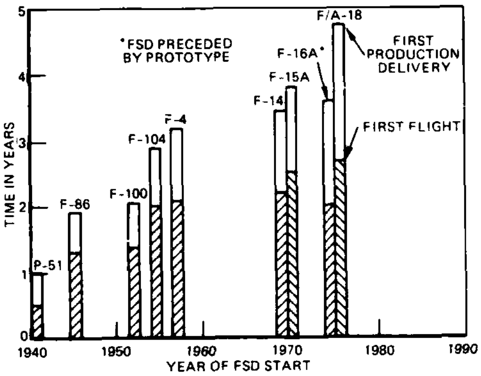

FIGURE 8. TIME AFTER FSD START TO FIRST FLIGHT AND TO FIRST PRODUCTION DELIVERY

The need to consider a balanced design in the face of conflicting requirements such as performance, reliability and maintainability, unit production cost, and weight, increases the number and depth of trade-off studies required and design decisions to be made.

Increase in structural fatigue life requirements causes enormous increases in the structural analytical task. The requirement to minimize weight, which is always the case in design of high-performance vehicles, requires reduction of safety margins, and as a result there is a high probability of a certain amount of redesign when full-scale laboratory and flight testing establishes changes in defined loads.

Where new materials are required to satisfy weight, stiffness, temperature, producibility, or low observables constraints, these materials will require characterization of standards and design allowables and the evolution of manufacturing process and tooling concepts, all of which must be fully developed before the end of FSD.

As the complexity of the aircraft increases in terms of on-board systems, numbers of weapons and stores to be carried and potential missions to be fulfilled, the test requirements to confirm satisfactory performance of all of these systems and functions are increased. The flight test program for a modern military fighter aircraft will require a significant number of test aircraft, each especially equipped for certain types of testing. Flight test cost has become a significant fraction of total FSD. The alternative of sequential use of the same aircraft for various tests, if feasible, might result in some cost savings, but would extend the length of the test program. Combined systems testing is required to confirm the proper performance of components in the system configuration (such as Iron Bird testing of hydraulics and flight controls or combined test of avionics, secondary power, fuel, or environmental control system components).

Advances in technology and complexity in military aircraft have also resulted in a transfer of a major share of the design and analytical activity away from the prime airframe manufacturer and into the specialized subcontractor world where the requisite expertise is resident. It is not uncommon today for 50 to 70 percent of the cost of a modern military aircraft to be procured by the prime contractor from subcontractors and

suppliers. Requirements for competition impose the need for evaluation and negotiation with multiple suppliers prior to award. This has increased the complexity of the communication task. The increasing percentage of FSD work done by suppliers and subcontractors for the airframe manufacturer adds to the level of supplier interface activity and its attendant cost, particularly for procurement, design, reliability, maintainability, and logistics specialists. The increases in cost and lengthening of time in the development process at the supplier will be affected by the same level of complexity and severity of requirements which causes this increase in time and cost for the prime.

POTENTIALS FOR IMPROVEMENT

The nature of the military aircraft procurement process indicates that the basic increase in FSD task complexity probably is unavoidable. However, there are potential gains to be made in reducing both time and cost by increasing the efficiency and effectiveness of the contractor's development process.

Of first importance is the avoidance of errors and the resulting time and cost required to redo tasks of all types. Although this type of problem is most often thought of in terms of scrap and rework impact in production, it can be potentially far more costly during development. One of the principal requirements for avoiding errors is the establishment of realistic schedules for tasks to be performed, allowing sufficient time for reasonable performance of work to be done. The main potential for achieving this end lies in properly developed, integrated (and followed) schedules for all aspects of the development program. Such integrated plans/schedules visible to all levels of program management can help ensure the best use of the time available by avoiding repeated tasks, maximizing parallel efforts, and ensuring the most efficient scheduling of sequential tasks. At Northrop, we have implemented a computer-driven integrated project management system using ARTEMIS, a program management software package developed in the U.K. This system is being applied to new programs and will significantly increase the ability to manage complex interrelated activities. Figure 9 shows a sample master program schedule which defines the timing of interrelated tasks.

One of the major causes of both missed schedules and significant cost increases is rework to correct errors made during all phases of the development process. The inherent conflict between hard program completion date milestones and the time normally required for completion of required sequential activities often results in artificial shortening of task schedules with the result that errors are made which later require correction. The approach of "doing it right the first time" is not just a slogan; it is a tangible approach to cost and time reduction. This makes realistic scheduling an absolute essential.

Since the end objective of a full-scale development program is the definition of a design amenable to repeatable and economic manufacture, it is exceedingly important to ensure Manufacturing Engineering involvement in the design development process. This was achieved on the F/A-18 program by collocation of manufacturing engineers within the design departments during initial design release and in major structural change activity to maximize the probability that designs, as released, would satisfy producibility criteria. The avoidance of redesign effort and its attendant delays and disruption in the development process provide significant potential for reduction in both cost and time required to achieve a fully released manufacturable design.

It has been shown in recent years that austere prototyping is an effective tool for reducing risk in development programs as well as total development cost. Although the exercise of a prototype program prior to FSD start adds time to the development process, it can reduce the time between FSD start and production deliveries. Figure 10 shows the time in months from the start of FSD or (prototyping) to delivery of the 200th production unit. The pattern shows an increasing trend with programs starting in the 1960s generally taking longer than 80 months from FSD start to 200th delivery. The A-10 and the F-16 shown on the right of the figure, the two recent USAF FSD programs preceded by prototype programs, show a significant reduction in the time from production delivery after FSD start compared to the trend line. The prototype phase provides additional time for demonstration and validation of new concepts.

The Air Force's newest program, the Advanced Tactical Fighter (ATF), will have a formal capitalized demonstration/validation phase, including design and the manufacture of flying prototypes. This demonstration/validation phase will permit an orderly entry into FSD with significantly reduced risk.

Control of technology risks before entering FSD should in turn ease the transition to production and reduce production costs. The key to technical risk reduction is the time required for new technology to mature. Preproduction development of multiple advanced technologies must allow time for alternate concept trade studies, for testing alternative components and assemblies, both hardware and software, and time for demonstration of integrated subsystems in their operating environment. To control risk reduction and properly use development time, a systems engineering tool is needed for line managers.

At Northrop, risk closure planning is established as part of the development process. Risk closure plans first recognize five stages of maturational development.

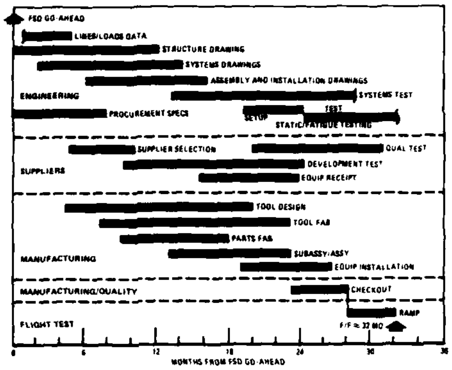

FIGURE 9. INTEGRATED FSD PROGRAM SCHEDULE

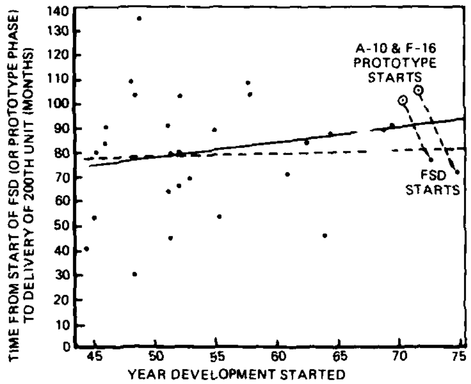

FIGURE 10. AIRCRAFT ACQUISITION INTERVALS SINCE 1944

The concept illustrated in Figure 11 has examined how risk and benefits can be evaluated within the bounds of DOD's A-109 procurement process. In the past, risk reduction has been focused on the FSD phase. Earlier risk reduction is possible with full employment of the demonstration/validation phase; much lower risks can result if prototypes are used to aid maturational development. While this opportunity exists within the procurement process, maximum benefits can accrue only if risk closure planning is employed in the early development phases. In the early phases, many alternatives can be assessed, parallel development plans can be established, and impact on national development resources, where limited, can be controlled. At Northrop, early technology assessment is employed to determine the match between new technologies and their technology insertion window during succeeding development phases.

For the ATF program, maturational development will be greatly accelerated by austere prototypes. Two prototype air vehicles will demonstrate new operational performance capabilities with many new air vehicle technologies. A ground-based prototype avionic subsystem will develop the total avionic suite based on VHSIC and other technologies. Additionally, other technology alternatives for FSD will be assessed in ground tests.

The second major step in Northrop risk reduction is the risk closure process illustrated schematically in Figure 12. Key elements of the process are as follows:

- Risk Identification, Assessment and Ranking. Technical concerns, both hardware and software, are assessed for maturity, complexity and dependency on others, and then ranked by functional managers.

- Risk Closure Plans and ARTEMIS Networks. Engineering plans are converted to critical path networks and iterated until preferred approaches, alternatives and fallback plans fit within program development milestones.

- Risk Closure Status and Risk Sensitivity Analysis. Risk control starts here when technical performance measures are established; tracking is combined with forward projections that closes on goals of reduced risk while also projecting schedule and cost performance for each risk issue. Sensitivity analysis provides visible feedback during development tasks to correct risk closure network schedules.

Periodic reviews are conducted to provide full management visibility, additional feedback, and to document risk closure progress.

With the multiplicity of the functional elements active on the development program, there is a high potential for duplication of effort by various disciplines. Schedules for the release of product definition data and the flow of such data through the system have typically been handled separately by the engineering and manufacturing disciplines. In addition to physical collocation, a restructuring of traditional methods to combine the various product definition activities as a collective discipline provides opportunity for specific savings. At Northrop, it is estimated that our newly developed system architecture to integrate the product definition discipline in the ATF program can result in a savings of four to seven percent of the engineering and manufacturing development effort and has the potential for taking as much as two months out of the design/manufacturing cycle. Figure 13 shows the position of the joint engineering/manufacturing/quality product definition activity in the total system. In this concept, activities which had previously been performed sequentially by these various functions

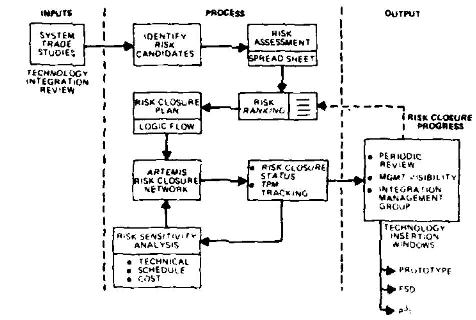

FIGURE 11. FIVE STAGES OF TECHNICAL RISK REDUCTION

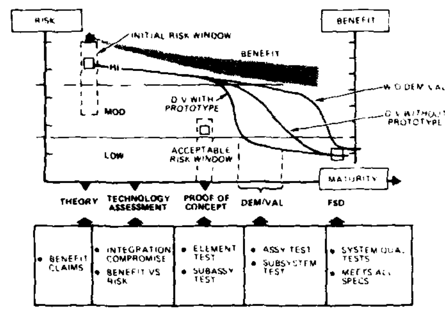

FIGURE 12. RISK CLOSURE PROCESS

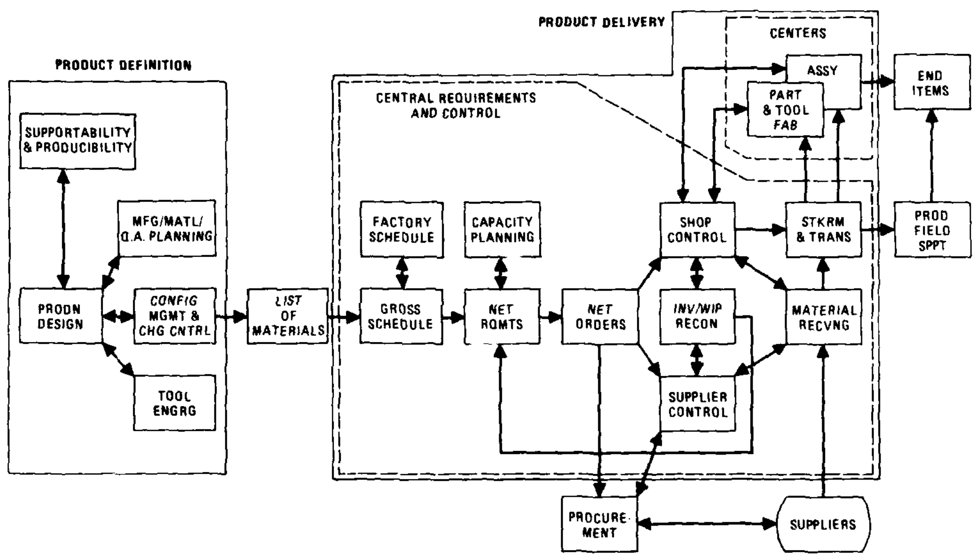

FIGURE 13. NEW DEVELOPMENT NORTHROP SYSTEM ARCHITECTURE

are now done concurrently under common management. It is estimated that this concept will reduce internally generated design changes by up to 75 percent.

A significant example of a traditionally repeated effort in the design and manufacture of machined parts for aircraft lies in the manual preparation of taped instructions for numerically controlled machine operations. This has typically continued to be the practice even after the development of computer-aided design (CAD) systems has permitted the definition of engineering designs in the form of digital computer data sets. Manual translation of engineering drawings by numeric-control programmers is potentially avoidable through the use of computer-generated machine instructions directly from the digital representation of the engineering configuration. The Northrop-developed MAXCAM system has been developed to provide automated translation of engineering design data directly into numeric machine instructions, effectively eliminating the manual programming task. It is anticipated that on a new aircraft development this could save as much as 30 percent of the direct and indirect non-touch manufacturing labor for machined parts.

The proliferation of high speed computation capability in the last 15 or 20 years has permitted the automation of many previously laborious manual tasks. Such activities

as computer-aided design, which reduces drafting time, and computer-aided engineering analysis generally have not reduced the total span time for engineering activity, but have enormously increased the number of tasks which can be performed within this span, as well as the depth and accuracy with which these tasks can be performed. This has permitted the refinement of designs by allowing for increased numbers of trade studies and the evaluation of design alternatives not previously possible. This has allowed a degree of design optimization which, although not apparently directly reducing development costs or time, has in the case of aircraft allowed the evolution of more efficient systems with increased durability, higher performance, better operational reliability, and reduced maintenance requirements. Three-dimensional computer graphics capabilities have enabled the optimization of space utilization by competing subsystems without the requirement for extensive, lengthy, and costly mock-up activities and have permitted the development of designs easier to manufacture and to maintain.

The development of "paperless systems," which can reduce flow time in all disciplines, has the potential for significant non-touch labor cost reduction and perhaps most importantly, reduces the potential for error in touch labor. At Northrop, on the F/A-18 program, implementation of the Integrated Management Planning and Control for Assembly (IMPCA) program has provided a means of eliminating the voluminous manufacturing planning paper associated with assembly operations. The flexibility and interdisciplinary usefulness of this system, we feel, is the way of the future. The savings potential in the F/A-18 assembly area is estimated at over 10 percent of the non-touch labor over five years. Figure 14 shows IMPCA versus traditional systems.

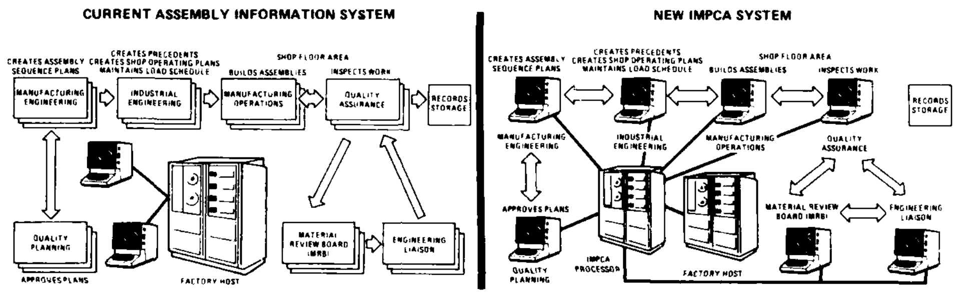

FIGURE 14. IMPCA "PAPERLESS" ASSEMBLY SYSTEM

Much of the development of factory robotics, although aimed principally at reduction in unit recurring cost, has applicability to and must be completed during FSD. Automated ply cutting and layup of graphite composite parts has been demonstrated on the F/A-18 program on rudder skins and the robotic assembly process is being extended for use in future programs. Figure 15 shows the F/A-18 rudder skin layup robot. Rudder skins have been manufactured at 75 percent cost and time reduction and without defects.

Robotic trimming and drilling of structural panels avoid the need for development of normal tools and is amenable to being programmed directly from basic engineering data. This system, developed for the F/A-18, is another example of elimination of conventional manual tasks by implementation of common data base usage. Figure 16 shows the robotic trim and drill system used for graphite/epoxy vertical tail skins.

FIGURE 15. ROBOTIC GRAPHITE/EPOXY SKIN PLY LAYUP

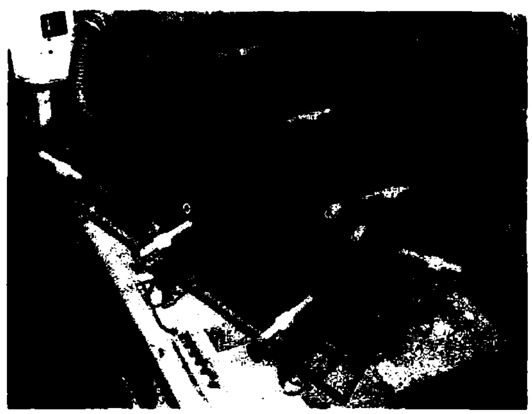

FIGURE 16. ROBOTIC TRIM AND DRILL TOOL

CONCLUSION

The total span of a full-scale development program from go-ahead to first flight and to completion of flight and laboratory test activity cannot be reduced beyond some rational minimum total time. Full-scale fatigue test of aircraft structures, for example, cannot be materially shortened. There are also minimum times associated with procurement of certain critical materials and some manufacturing activities. However, in all phases of the development process, the potential for reduction in manual tasks through the use of thoughtfully applied automated systems and the increases in efficiency through sharing of common data bases throughout the development process show potential for arresting the escalating costs of full-scale engineering development of modern military aircraft. Changes in the past 10 years have shown beneficial effects in the fielding of aircraft systems with significant gains in performance, reliability, and maintainability as well as unit production cost control. The use of pre-FSD demonstration/validation programs with austere prototyping is the means for reducing FSD risk and cost; it also shortens the required span from FSD start to production delivery. The continued infusion of computer-aided activities in the development process shows promise for additional improvements in the efficiency and effectiveness of FSD activities.

REASONS FOR INCREASING DEVELOPMENT COST OF ROTARY WING AIRCRAFT AND IDEAS TO REVERSE THE TREND

by

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SUMMARY

In the first part of the paper general cost trends of complex systems, such as helicopters, are described. Then the influence of requirements and complexity on cost of helicopters are discussed. After an analysis of cost trends and of negative effects relativ to helicopter development cost ideas to revert the trend are presented. In this context besides the generally used classical methods of good engineering practice other methods, such as cost engineering and international cooperation, are dealt with. In summary good engineering judgement combined with proper planning and management still is the best method to keep cost under control.

1. PRINCIPLES AND GENERAL TRENDS

Before concentrating on the subject of development cost, it is useful to explain some important principles and general trends relative to costs of complex systems.

1.1 Basic Information about Cost Trends of Complex Systems

Although a high number, development cost of complex systems, such as military helicopters, is only in the order of 5 - 10 % of the total cost. Normally 50 - 70 % of the total cost are related to the operation and support of the systems (see fig. 1). This can be demonstrated also in actual figures by the cost distribution of typical Defence Budgets (fig. 2 shows the Defence Budget of Germany for the year 1982).

Another important feature is the fact that the total costs (LCC) get locked in relatively early in a programme. Only when a few percent of the total costs are spent over 70 % of the LCC are committed (fig. 3). In addition, modifications to the system are relatively inexpensive only in the early phases of a programme(fig. 4).

Fig. 5 shows another important trend concerning cost of development of complex systems. Sticking to extreme requirements may become very expensive. At a first glance this looks trivial but, nevertheless, this was one of the main reasons why programmes got and are getting into problems. Getting a good understanding of the sensitivity of requirements relative to cost is very important before the final requirements are frozen. Another reason to invest into the early phases of complex programmes.

Fig. 5 indicates another interesting tendency of complex programmes. If the development contract price type is "cost plus" one tends to stick to the requirements (point B), whereas one naturally tries to keep the cost constant in the case of a firm/fixed price type of contract (point C).

These generally valid trends are the explanation of the relative importance of the early phases of complex programmes. If we discuss the costs of the development phase we should not forget this trend. Unbalanced cost savings in the early phases of programmes can become later very expensive. There is also a natural tendency to concentrate on development cost reductions because systems being in operation are normally not touched anymore. The same is also true, at least in Germany, for production of complex systems because these are normally performed in international cooperation (Airbus, Tornado, Ariane, etc.).

1.2 Mass Amplification Factor and Necessity for Light Weight Design

For aircraft and especially for such with VTOL-capability, light weight design is very important. Costs for the aircraft and for the carrying out of the payload transportation are strongly influenced by the mass empty of the a/c and the mass empty, M_E, is influenced by the selected technology (see fig. 6). Similarly at least part of the DOC is influenced by the mass empty and the selected technology as well (fig. 7). In this context, the mass amplification factor ε of an aircraft is of special importance. Fig. 8 gives the relevant definitions concerning mass elements of aircraft and fig. 9 shows the mass

amplification factor ε as function of M_E/M_A for an aircraft. That means, if you add one unnecessary kg to your aircraft, the take-off mass has to be raised by ε kg, if you do not allow to reduce the performance level. On the other side, if you can reduce the masses one kg by the use of new technologies, take-off mass of the considered aircraft will be ε kg less. As shown in fig. 10 the take-off mass M_A of the PAH 2 antitank helicopter could be reduced by about 15 % if one could accept a single man cockpit. The size of ε gives also an indication about the involved complexity and has a significant influence on the necessary development cost. Configurations with high factors ε, for example, are much more sensitive to weight and drag increases which to a certain degree will develop during the life of a complex system.

1.3 Trends for Development Cost of Helicopters

Although the necessary development costs for a helicopter depend on many elements, which have nothing to do with the machine - such as experience and size of the design team, inflation, labour rate, etc. - some trends can be given:

- According to fig. 11 the size of the helicopter and of course the complexity/performance level have a significant influence.

- Mass amplification factor ε, as already mentioned, speed, empty mass, hover and cruise efficiency are of importance relative to development cost (fig. 12, 13 and 14).

The driving factors for development cost of helicopters depend mainly on the requirements/performances:

- payload/range/speed
- hover and cruise efficiency
- reliability and safety
- maintainability

For all extreme requirements the principle of fig. 5 is valid.

2. ANALYSIS OF DEVELOPMENT COST TRENDS

Because no company is eager to publish its own cost overruns and because the information given in the newspapers and magazines often compare "apples with potatoes", it is difficult to find valid and fair data concerning actual development cost. It also makes a big difference, in comparing such cost, which type of price is used (cost plus, fixed/firm price) and to which degree punishments are imposed on the contractor in case certain performances are not met. The rules of the civil business in this respect are clearer. The competitors and the operators tell you how far you have to go to survive on the market.

Even when one subtracts inflation, it must be accepted that helicopters have become more and more expensive and some machines approach already the unit cost of high performance fighters. Although fig. 15 gives only published examples of US products the same tendency is true for European products. A similar trend is valid for development cost of new helicopter programmes, such as LHX, PAH 2, JVX etc. Concerning development time schedules there is a tendency to underestimate the development of a new helicopter, especially if you compare it with the development cycles of civil transport aircraft. To make this clearer, in fig. 16 the only two milestones of civil programmes which are fixed and cannot be manipulated - date of first flight and date of certification - are compared. As you can see, helicopters need more time and the scatter of the different programmes is much more pronounced. This is a strong indication that developing a helicopter depends more on trial and error. Therefore, probably the actual development cost of helicopter programmes also have more scatter. The methods to predict development cost of helicopters still seem to be less accurate. Whether this is inherent in the helicopter itself or whether only missing data/information are the cause is difficult to judge. But fig. 16 clearly shows the need to look into this subject. Fig. 17 lists a variety of generally negative effects relative to development cost. Some of these effects are "facts of life" and cannot be changed by a design team. Those effects are an explanation why the costs have increased with time.

But there are also negative effects which can be influenced by proper management. Even considering that there is no "ideal world" in practical engineering and that one has to live with compromises, here are the spots where the improvements must start.

3. IDEAS TO REVERT THE TREND

3.1 Classical Methods (Good Engineering Practice)

The design team can influence all relevant costs (unit production cost, LCC, DOC and cost of the development phase). Concerning the development phase three groups of activities have to be mentioned.

3.1.1 General Methods to Reduce Development Cost

Fig. 18 lists important general effects relative to development cost:

- Most important are all the effects related to your personal (team). Although it is difficult to quantify in absolute numbers the most meaningful investment a company can do is to invest into the people.

- The use of modern tools has to be seen in combination with the number of manhours. For expensive modern tools (CADAM, supercomputers, manned simulators) working around the clock has a positive effect. However, working in shifts in engineering departments is against the general trend in Germany and therefore difficult to achieve. It is not a simple task to find the right balance between the amount of manhours and the cost for automatisation (use of expensive modern tools). But here is another key to reduce cost of development work (principle see fig. 19).

- The use of computers - on the one side being a great help - has the danger to "overdo" things and not to reduce, but create costs. Fig. 20 is an illustration of this problem by comparing the pressure distribution of an airflow around a sphere which was produced by three methods. An important question in this respect is how much accuracy is needed and how accurate are the used input data.

- The methods to reduce the risks of development are schematically explained in fig. 21. On the other hand going high risk and being lucky can safe a lot of money but that is not my recommendation for the development of helicopters.

- Fig. 22 shows the optimum timing of the development of a complex system. By proper planning and management one tries to approach this ideal as close as it is possible in the "real world".

The above discussed general effects have the most important influence on the performance of development work. It is impossible to give generally valid rules which can be used all over the world because each programme has its own specific random conditions and problems.

3.1.2 Reducing Cost for Carrying out Routine Work

Fig. 23 shows the most important routines one has to carry out during the development phase of a helicopter. This picture makes in my opinion very clear how big the potential of the mentioned modern tools really is. However, it shows also the danger. One may be forced by the competition or the requirements to use the modern tools to do even more thorough investigations and increase the amount of data i.e. produce more work than the time which can be safed.

3.1.3 Carrying out the Innovative Part of Development Work

This part of the work is very difficult to plan. For innovations one has to create the right climate. A main key is the motivation and job dedication of your team. It is sure, putting in only money in form of good salaries, is not the solution.

3.2 Cost Engineering Methods

Fig. 24 gives a list - by far not complete - of different methods to reduce cost which have been used and which are described in the literature. The advantage of these methods is that a certain systematic approach has to be used. But there are also drawbacks and classical mistakes have been repeated at many instances.

- First you need a lot of good engineers to do design reviews, value engineering studies and so on. Normally these engineers are better used if they play an active role in carrying out the development!

- Secondly if the timing and/or organisation for such activities is wrong no costs are safed but additional costs are created.

- There is the danger to optimise only into one direction (aiming towards min. cost) and to prefer unproper solutions (A not properly set up value engineering team would probably reinvent two blades sea-saw rotors and fabric covered wooden airframes!)

Each engineer with a proper engineering education is trained such that he tries to find the least expensive solution for a required task. As a consequence an engineer normally is not against the cost minimum, as long as he has the relevant data and knowledge available. This fact and probably the mixed experience with the classical methods led to new disciplines with the aim to support the development engineers (DTC, DTLC). Today, as a final step, one tries to develop a strategy and make best use of all cost safing methods togethe One can name this discipline "cost engineering". Many companies install own groups which have the responsibility to create such cost information and train development engineers on the job, while creating and updating the relevant data base. So do we at MBB at the level of the different divisions and for support and coordination in addition centrally. Fig. 25

gives a typical example out of MBB's experience. You can also find many other examples in the literature.

The advantages of such a data base would be amongst others:

- Possibility for a systematic analysis of the cost of certain features incl. the cost sensitivity of requirements with the aim to eliminate cost drivers.
- Possibility to support classical cost estimates by analytical methods with the aim to come to more accurate cost predictions (see fig. 26).
- There are also computer programmes available to calculate cost data for complete complex systems. For example at MBB the widely used PRICE programme is adjusted to the MBB specific environment.

To be honest, we still have a wide way ahead of us until we have a complete and reliable data base. Nevertheless, the potential of the cost engineering discipline is very important to revert the cost trend.

4. INTERNATIONAL COOPERATION

A simple possibility to reduce development cost is international cooperation. Although the overall costs for a development programme are higher, mainly because the joint requirements will probably be more stringent as in the case if one does it alone and also certain friction losses and duplications have to be accepted, one partners share is reduced significantly. This was demonstrated in Europe on many occasions and my company MBB has many good experiences with such programmes. Very recently, in the context with the international NH 90 study which was performed jointly by AS, Agusta, WLH, Fokker and MBB the subject of safing non recurring cost by international cooperation was studied again.

Fig. 27 gives in condensed form information about the percentage of cost which can be safed per partner and the amount which can be lost when partners can not agree to full standardisation. Accordingly the practical optimum is probably a cooperation between 2 or 3 partners. The possible gains by more partners can easily be lost by the difficulties reaching agreement. The problem in reaching or not reaching joint compromises can be demonstrated very drastically if you consider the current situation in Europe in respect to the military helicopter requirements and the potential future programmes (see fig. 28). It seems to me that national pride still is more important than budget problems.

5. SUMMARY AND OUTLOOK

Cost of development of complex systems, such as helicopters, is a very difficile subject as I hopefully could demonstrate a little bit. The main conclusions how to tackle the cost problem are listed again in fig. 29. In summary good engineering judgement combined with proper planning and management is still the best method to keep cost under control. Sorry that I do not have a better answer. I would like to conclude with a picture showing a helicopter flying over the plexiglas "tent" which covers the area which was built for the olympic games 1972 in Munich. The cost overruns of this project were an order of magnitude higher compared with "famous" cases of our industry including my own experiences. I selected this example not to excuse us or blame others, just to demonstrate that this problem is with all of us. If you make the classical mistakes it is not possible to build a house within the projected cost, although mankind built houses since ever.

6. ABBREVIATIONS

LCC	life cycle cost
R & D	research and development
PD	project definition
RDT & E	research, development, test and engineering
DOC	direct operation cost
TBO	time between overhaul
ATH	Attack Helicopter
XSMN	transmission
VTOL	vertical take off and landing
V_{max}	max. speed
CADAM	computer aided design and manufacture
2 D	two dimensional
3 D	three dimensional
DTC	design to cost
DTLC	design to life cycle cost
PPPI	preplanned product improvement
LLTI	long lead time items
MMH/FH	maintenance manhour per flight hour
BIT	built in test capability
WBE(i)	work break down element (i)
NRC	non recurring cost

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[3] G. Reichert, Helicopter Aeromechanics
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[4] Flight

Relative Cost and Lifecycles of Complex Systems

Fig. 1

	Aircraft & Helicopter	Tank & Ship
Concept, Definition, Development	1.0	0.5
Production	3.0	2.5
Operation	6.0	7.0
Σ	10.0	10.0
Lifecycle (years)	25 . . . 30	25 . . . 30 30 . . . 35

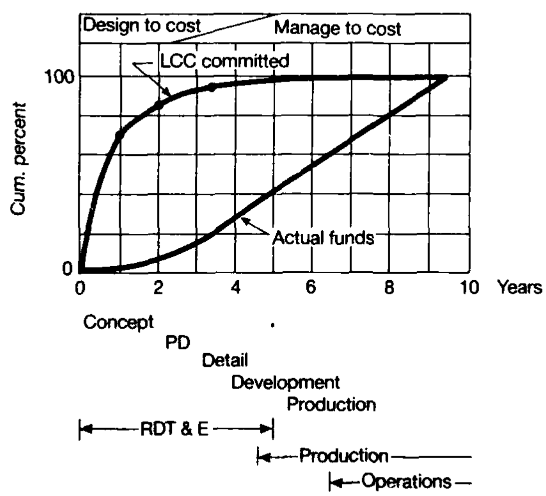
German Defense Budget (1982)

Fig. 2

	Billion DM	%
R & D	1.6	4
Procurement	9.4	22
Operation	20.0	48
Personnel	11.0	26
Σ	42.0	100

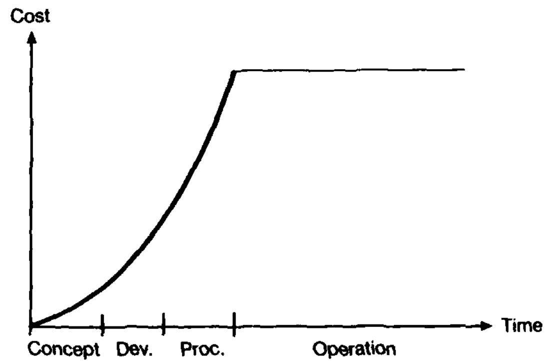
LCC Gets Locked in Early [1]

Fig. 3



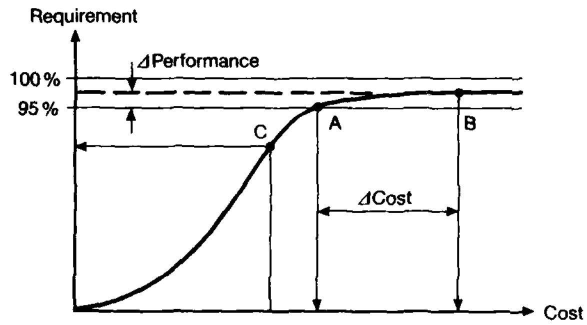
Effect of Time of Design-Modifications on Cost

Fig. 4



Danger of Design to Requirement

Fig. 5



Important Cost Relations [2]

Fig. 6

Unit Cost of Helicopter	Cost Trend for Payload/Range
$\frac{C_1}{M_A} \sim \frac{M_E}{M_A}$	$\frac{C_2}{M_A} \sim \frac{1}{M_{PL}} = \frac{1}{M_A - M_E}$
$\frac{M_E}{M_A}$ = f (Technology)	$\frac{M_{PL}}{M_A}$ = f (Technology)

Consequence:
- Light weight design
- Advanced technology

Factors Influencing Doc [2]

Fig. 7

- Capital investment — Depreciation, Interest rate, Insurance — $\frac{C_3}{M_A} \sim \frac{M_E}{M_A}$ = f (Light weight design, technology)

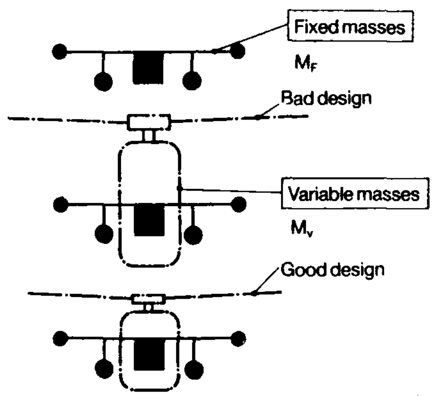
- Support cost — Maintenance, Repair, Spares — $\frac{C_4}{M_A}$ = f (TBO, technology)

- Fuel & lubricants — $\frac{C_{FUEL}}{M_A} \sim \frac{SFC}{\left(\frac{M_A}{N}\right)}$ = f (Light weight design, technology)

- Crew — $\frac{C_{CREW}}{M_A}$ = f (Technology)

Definition of Different Masses [2]

Fig. 8



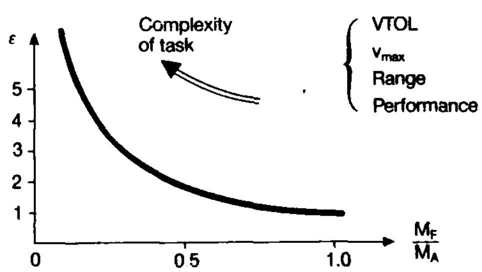
Fixed masses:
- Payload — M_{PL}
- Crew — M_{CREW}
- Fixed equipment — M_{MEP}
- Mission equipment package

Variable masses:
- Rotor & XSMN — M_{dyn}
- Airframe, equipment & landing gear — $M_{Airf.}$
- Engine — $M_{Eng.}$
- Fuel — M_{Fuel}

➡ Lightest/smallest aircraft is normally least expensive solution (min. **LCC**)

Importance of Factor ε [2]

Fig. 9



$$\boxed{M_A = M_A \pm \varepsilon \cdot \Delta M}$$

Reduction of Masses by Use of New Technologies (Single Man Cockpit for ATH)

Fig. 10

- Reduction of masses by use of new technologies at the beginning of a new development takes full benefit of factor ε

  → Multipurpose helicopter $\Delta M = 1\,kg \rightarrow \Delta M_A \approx 2.0\,kg\ (\varepsilon \approx 2.0)$

  → Advanced attack helicopter $\Delta M = 1\,kg \rightarrow \Delta M_A \approx 3.0\,kg\ (\varepsilon \approx 3.0)$

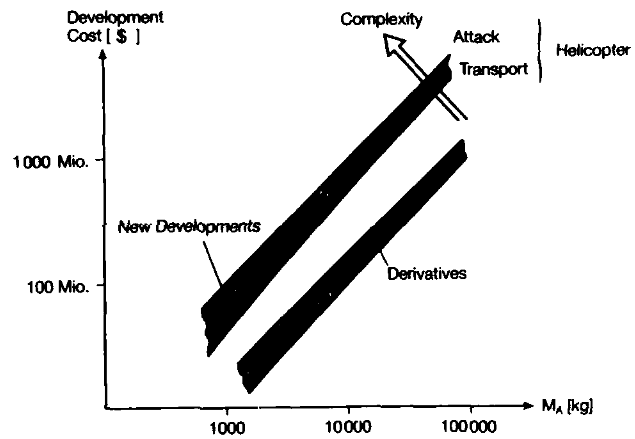
- Required fixed masses incl. MEP much more important for attack helicopter than for multipurpose helicopter:

  PAH 2 with one man cockpit: $5000\,kg \rightarrow 4200\,kg: \Delta M_A \approx 15\,\%$

  Navy helicopter with 2 crew-members instead of three $8000\,kg \rightarrow 7600\,kg: \Delta M_A \approx 5\,\%$

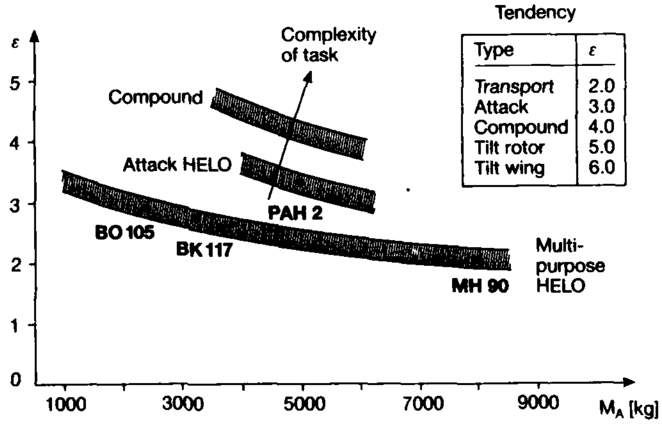
Trend of Development Cost of Helicopters

Fig. 11



Factor ε for Typical Rotary Wing Aircraft Configurations [2]

Fig. 12

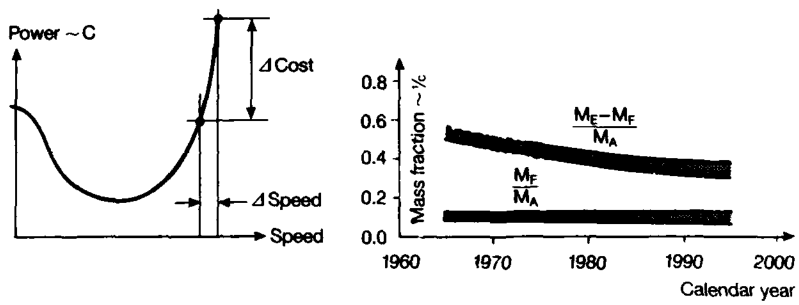


Tendency

Type	ε
Transport	2.0
Attack	3.0
Compound	4.0
Tilt rotor	5.0
Tilt wing	6.0

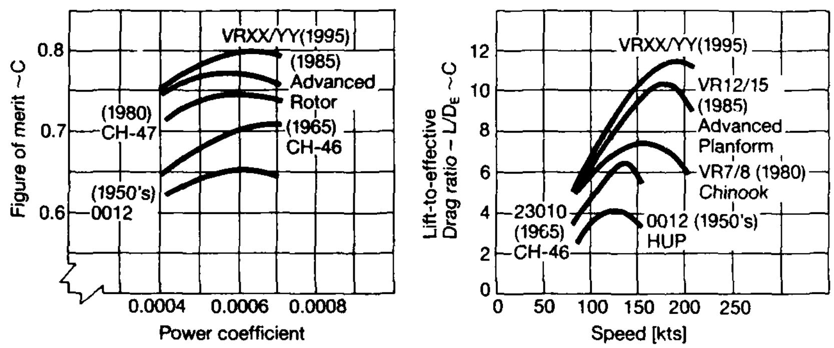
Power Requ. as Function of Speed (Typ) and Trend of Payload [3]

Fig. 13



Hover and Forward Flight Efficiency [3]

Fig. 14

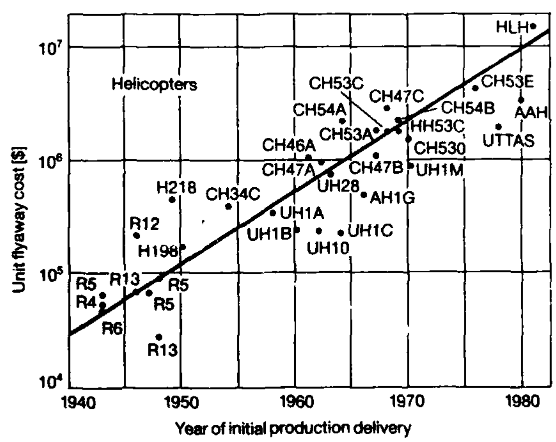


Typical Cost Information About Helicopters [3, 4]

Fig. 15

US Equipment Unit Costs, 1984 Budget

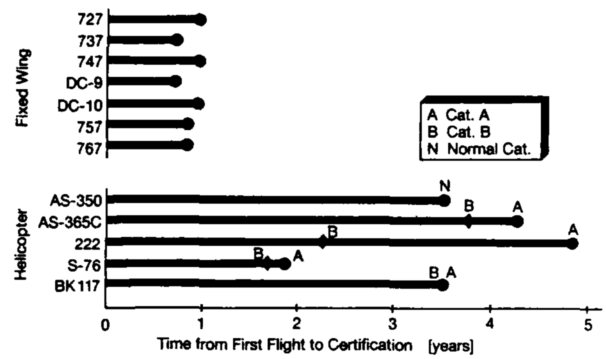
	Unit flyaway cost, $ million (number to be purchased in 1984)
US Air Force	
Rockwell B-1B	419.5 (10)
C-5B Galaxy	286.5 (4)
KC-10A Extender	67.9 (8)
Lockheed TR-1	42.7 (5)
MC-130H Hercules	34.1 (2)
US Navy/Marine Corps	
EA-6B Prowler	66.6 (7)
E-2C Hawkeye	55.2 (6)
P-3C Orion	52.8 (5)
EP-3 Orion	50.9 (2)
F-14 Tomcat	45.4 (24)
A-6E Intruder	35.6 (7)
F-18 Hornet	28.1 (84)
AV-8B Harrier II	27.2 (32)
→ **SH-60B Sea Hawk**	**26.1 (21)**
C-2 Greyhound	23.4 (8)
→ **CH-53E Sea Stallion**	**20.4 (11)**
US Army	
EH-60A Quick-Fix II	12.0 (12)
AH-64 Apache	11.9 (112)
Missiles	
MX Peacekeeper	102.6 (27)
BGM-109G Tomahawk	5.0 (120)
MGM-31 Pershing II	4.3 (95)
BGM-109A Tomahawk	2.9 (124)
MIM-104A Patriot	1.9 (525)



→ Development cost have a similar tendency

Comparison of Development Time of Fixed Wing and Helicopters [4]

Fig. 16



Neg. Effects Relative to Development Cost

Fig. 17

Difficult to Influence

- Inflation
  Salaries
  Cost of materials
  Cost of energy
- Customer requirements
  Certification requirements
- Improved performances
  Reliability, safety, servicelife
- More avionics & software
- Democracy requires time for decision making
- Specialised configurations
- Too many programmes and different customers

- Constant level of personnel (no hire & fire)

  Too many specialists (missing flexibility)

  No adequate personnel structure (missing software experts)

Can be Influenced

- No definition phase
  Overspecification
  Overdesign
  Optimisation of details
- Too optimistic cost estimation
  Too high technical risk
- Changed requirements
- Underestimation of software
- New technologies → improved performances
- Bad management
  Not adequate planning
  Too slow decision making
- Mistakes
- Growth of data output
  Uncontrolled flood of paper

General Positive Effects Relative to Development Cost

Fig. 18

- Capacity peaks → Work overtime
  → Contract engineers
  → Subcontracts
- Quality → Training programmes
  → Job rotation
  → Hire young people
- Motivation → Small teams
  → „Delegated resp."
  → Clear organisation

Balanced use of modern tools

- Computer simulation
- Windtunnel models & component tests
- Super computers & manned simulator
- Flying simulator
- Experimental a/c & prototypes

Balanced use of computers

- CADAM (2D & 3D)
- Online info & planning systems
- Text systems
- Automated analysis of tests
- SW tools
- Failure mode analysis

Reduction of risks

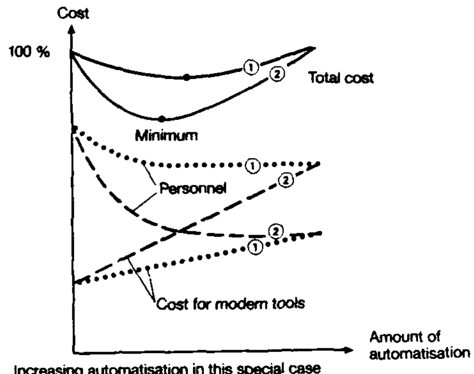
- Early design & technol. verification testing
- Fallback solutions in critical areas
- Critical software by two teams
- More time for early phases

Proper planning & management

- Perform definition phase (techn. definition & planning)
- Concentrations on important matters
- "Buy" technology if less expensive (do not reinvent the wheel)
- Design/config./spec. freeze
- Flexible programme management
  → Small teams
  → Control of performance, time & cost
  → Use "early warning systems"

Balance Use of Modern Tools and Personnel (Principle)

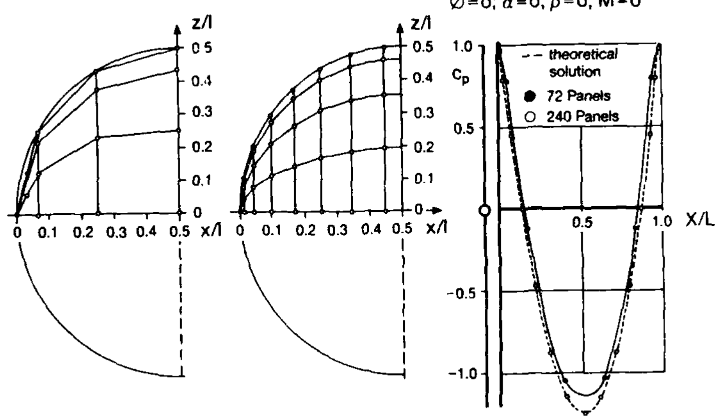
Fig. 19



Increasing automatisation in this special case would allow to reduce the personnel accordingly.

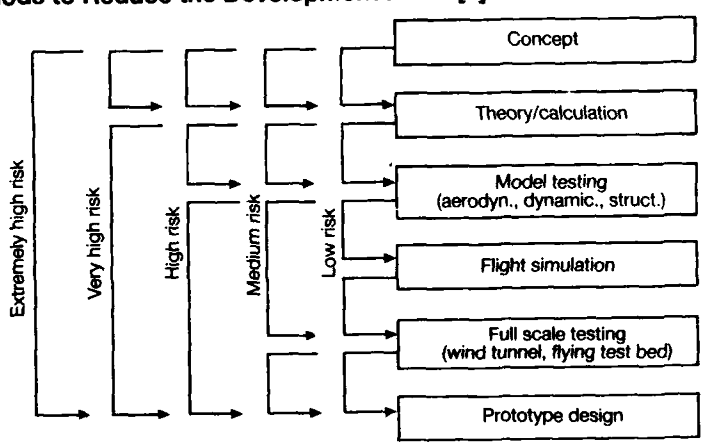
Balanced Use of Computer Programmes

Fig. 20



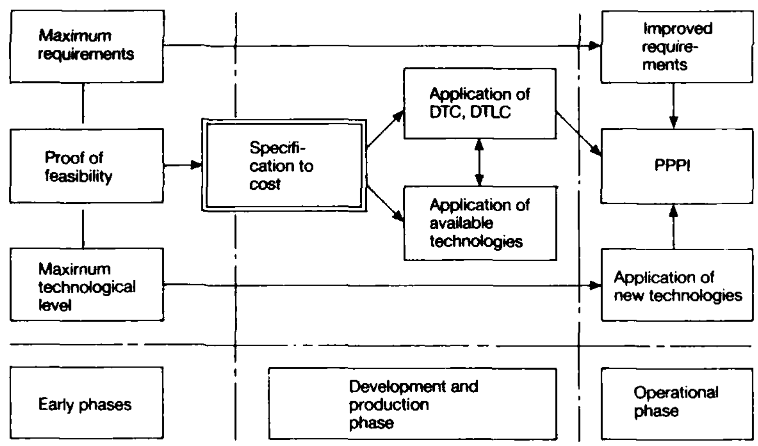
Methods to Reduce the Development Risks [3]

Fig. 21



Optimum Timing of the Life Cycle of a Complex System

Fig. 22



Main Elements of Development Work

Fig. 23

	Layout	Prototype design & fabrication	Proof of compliance certification	Reporting
Software	Drawings (preliminary design) Assessment of mockups Calculations (layout) Planning of tests Wind tunnel tests System architectures Performance of design verification tests ↓ • Prepare drawings • Use computer programmes • Write Reports	Drawings Spec's Standards Changing of doc. design verification tests ↓ • Prepare drawings • Write reports • Translate • Stress calculations • Acceptance tests	Proof by theory Proof by test Proof by failure mode analysis Prepare certification documentation ↓ • Performance of tests • Analysis of tests • Writing reports • Carrying out calculations • Prepare drawings • Translations	Intern → min. Extern → customer ↓ • Write reports • Prepare drawings
Hardware	Mock ups Wind tunnel models Test specimen Test equipment Infrastructure Order LLTI	Prototypes Tool & Jigs Test specimen Test equipment Order bought out items	Acceptance test of bought items Test equipment Infrastructure	

Modern Methodologies

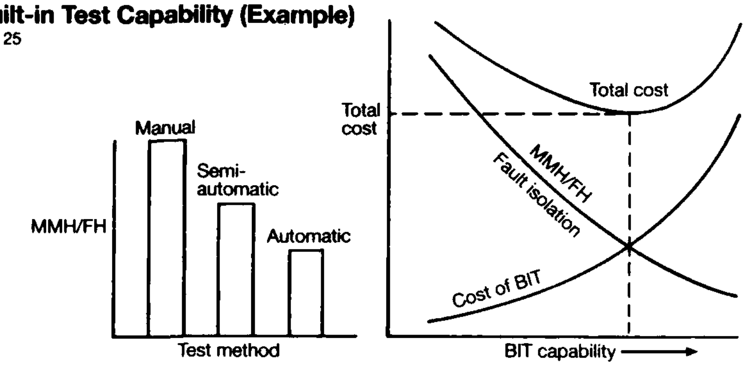
Fig. 24

- Generally known & used methods
  - Brainstorming
  - Design reviews
  - Optimum design methods
  - Systematic & analytically valued comparison of different solutions
- Value engineering
- DTC
- DTLC

→ Cost engineering

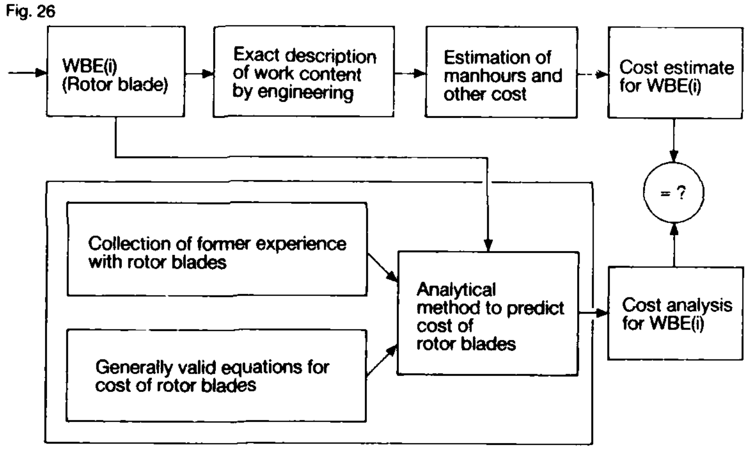
Optimisation of Automatic Built-in Test Capability (Example)

Fig. 25



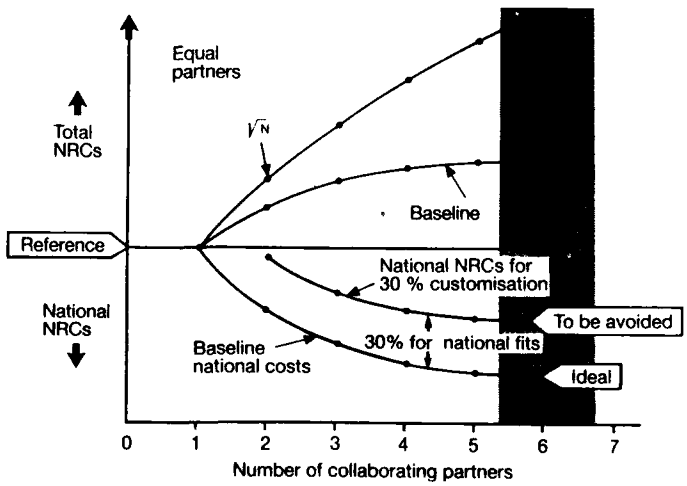
Principal How to Improve Cost Predictions by Cost Engineering Methods

Fig. 26



Effects of International Cooperation on Nonrecurring Cost of Helicopters

Fig. 27

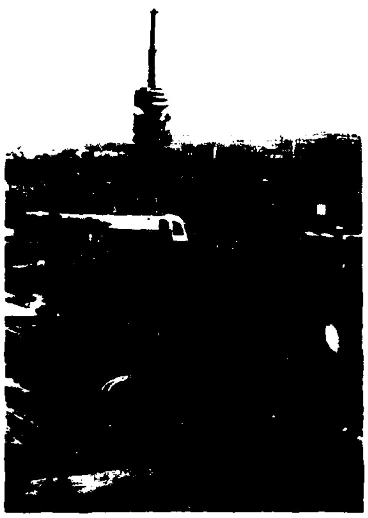


Who Collaborates with Whom?
Fig. 28

	NH 90	CATM (PAH 2)	EH 101	A129 (Tonal)
Britain			●	●
France	●	●		
FRG	●	●		
Italy	●		●	●
Netherlands	●			●
Spain				●
Number of required helicopters	500	400	100	200

Main Conclusions
Fig. 29

- Design approach is major cost driver
- Design for unit production cost targets, minimum LCC and development cost targets
- Develop cost engineering as a primary **engineering discipline**
  - control requirements to mission essentials
  - control sophistication
  - identify high cost designs systematically and revise design approach
  - increase standardisation
  - cost to have equal importance relative to performances and weight
  - allocate target costs to WBEs
  - develop and utilize facilities for reduction of cost risks
  - develop usable cost information database (manuals, analytical cost models, complete programmes, etc.)
- Engineers responsible for technical/cost of design
- Engineers motivated and rewarded for design to cost
- Minimize facility and other overhead costs



"The Judgement and Evaluation of Long-Term Investments
Demonstrated by Means of a Civil Aircraft Program"

by Dr. W. ZABKA (MBB GmbH, Germany)

1. INTRODUCTION

The economic characteristics of the civil aircraft industry are somewhat unique in terms of the magnitude of investment and the risks involved. Civil aircraft programs represent comlex risk ventures that are accomplished in an environment of constantly changing market conditions, competitive actions and technological alternatives. The objective of this lecture is to demonstrate the particular economic aspects of the civil aircraft industry, which are to be taken into account, when preparing a decision for a new aircraft program.

The subjects discussed are organized under three major sections. The first provides a short overview of the economic realities of the civil aircraft business. The second major section of this presentation focusses on how to comprehend adequately all these factors in one transparent calculation in order to describe the main criterial milestones in a civil aircraft program, with special emphasis on financial aspects. The question to be answered in this part is: What are the criteria for judging such a program?
The third section deals with the separate discussion of the influencing factors and their changes. The question to be answered in this section is: How does the risk and the economic success of a program change if one factor changes. Special emphasis is put on the impact of the development costs and the development lead-time.

2. ECONOMIC PARAMETERS

The economic environment of civil aircraft production is quite fascinating. A unique combination of characteristics makes this industry a high-risk business. These unique characteristics include relatively low production volume, large swings in production rates, high development or launch costs, long development lead-time, extensive work allocation and industrial specialization, a dynamic unit cost pattern, and a difficult competitive environment. Any one of these factors would inject a high level of business risk. However, the compounding of risk when all are acting in concert, makes the industry unique.

Commercial aircraft production requires an extremely large initial development investment. The non-recurring costs of designing, developing and fabricating tooling and certifying a typical new medium-sized airplane are today approximately $ 1.5 billion. These are only the non-recurring development or launch costs. They exlude the recurring inventory manufacturing costs incurred prior to first delivery, which are about equal to the development costs. Thus, it is apparent that the launch costs alone represent a tremendous risk and can be recovered only through high production and sales volume.

The development involves some other risks. The market requirements must be anticipated many years in advance, owing to the long development lead-time and pay back period both increasing the uncertainty. On average, it takes approcimately 4 years from program go-ahead to first delivery. This in return results - besides market risks - in an additional increased financial risk owing to capital cost. In the just mentioned example of $1.5 billion development costs, the capital costs amount to some 30 % of the nominal development costs within 4 years, depending on the rate of interest.

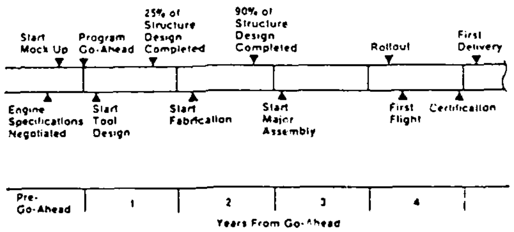


Fig. 1

Typical Commercial Jet Transport Aircraft Development Flow Time

The other major cost element of a program is the recurring costs. These are subjected to the cost-degression phenomenon. This results in high initial unit costs, that diminish successively with units produced. The degression curve reflects the reduction in unit man-hours that occurs with the repetition of operations. The rate of improvement is also determined by the type of tooling and level of automation involved. Because the cost degression depends largely on the accumulated production volume, it is obvious that this cost phenomenon is a reason for the statement that programs with a relatively small number of aircraft produced must fail.

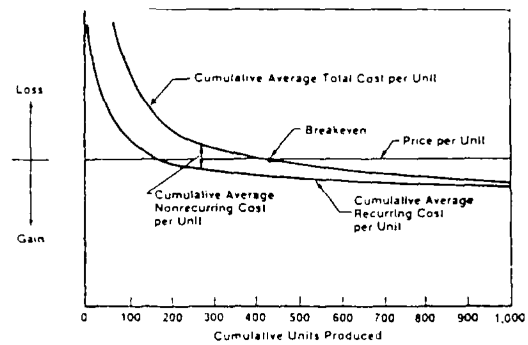


Fig. 2

Airplane Price vs. Cost

To sum up: high development costs, high inventory, cost degression and long development lead-times, producing development risk and an additional high cost of capital, are inherent cost- and risk-drivers originated by the *manufacturer.* It takes a long time, and a substantial production volume, to amortize the initial development investment, as well as to bring the *unit cost* down sufficiently to permit such amortization.

A brief look at the number of total aircraft deliveriesper year in the past indicates that there exists only a very small market potential expressed in units. From this one can derive that the minimum required production volume limits the number of producers that can be sustained by the market on a profitable basis.

There is a direct interrelationship between traffic fluctuations and aircraft orders. Relatively minor fluctuations in traveler demand are strongly amplified, since the airlines want quick delivery response to surges in traffic growth. Conversely, the airlines cancel or defer orders when traffic diminishes. One example is the 707 program which dropped from an annual production rate of 118 to ' aircraft between 1967 and 1972, a period of just 5 years. Similar fluctuations are av dent for all known aircraft programs. The effect is twofold: first increased, unplanned cost of capital, and second in the case of rapid increasing production, unpredicted negative changes of the cost degression characteristic.

Flucations in total annual volume do not occur in terms of individual programs only, but are also evident in the industry as a whole. The total units for all the programs produced by all US and European manufacturers peaked at 741 in 1968, and dropped to 250 only 3 years later.

Another risk in developing a new aircraft is the demand oligopoly, that means a concentration of the substantial market potential an a limited number of airlines. There are about 300 airlines in the free world that operate jet transport aircraft. 25 of them with partially adverse requirements account for more than 60 % of the world's traffic, while 50 airlines account for 75 % of the total. Because of this demand concentration in a relatively small number of airlines, the degree of success achieved by aircraft producers depends largely on the level of sales to these major carriers. This in turn depends on the performance of the aircraft as defined by the design and development departments, in order to cover as many requirements of as many customers as possible.

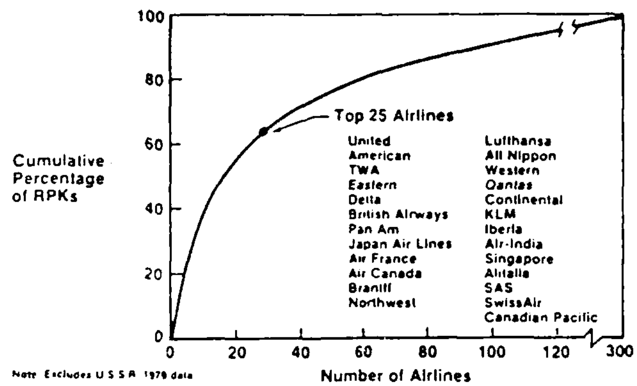


Fig. 3

Concentration of the Airline Industry

3. CASH FLOW OF A TYPICAL CIVIL AIRCRAFT PROGRAM

The object of this lecture is to present an evaluation model for long-term investment decisions, and to apply it to the planning of a civil transport aircraft in order to provide a better understanding of the financial repercussions resulting form changes of the tangible parameters. Although it may seem unnecessary, I would like to state that the uncertainty of future environment changes cannot be eliminated by an improvement of mathematical models.But, *precisely because of the high uncertainty*, one has to determine the impact of every factor on the planned objective as accurately as possible in order to obtain a good understanding of the risks involved.

The evaluation method for judgement of long-term investments as decribed in the following avoids many disadvantages of the commonly used methods, e.g. Net Present Value and Internal Rate of Return. These methods reduce the decision on one figure only.They are inaccurate owing to the assumption of reinvestment and cannot distinguish between different financing shares.

The here presented method is called "Modified Cash-Flow". It distinguishes between the proprietary capital and financing with borrowed money including resulting interest. The propietary capital itself is part of the cash-flow, but the rate of interest to be achieved is a management decision, and does not occur in reality. This portion of cost is called imputed interest and does not contribute to the actual cash-flow. But, imputed costs - respectively the RETURN ON NET WORTH - are the most essential characteristic for judging a long-term program. After repaying the loan capital inclusive interest, the imputed costs have to be covered by the annual distribution margins. When their accumulated value beyond the break-even point is identical with the planned accumulated gain, the program target is achieved.

The evaluation model is based on the cash-flow of the tangible characteristics as presented in diagram 4. The numerical example is carried out with the figures of this diagram, representing a hypothetical medium-sized civil transport aircraft.

NUMERICAL EXAMPLE - "Reference Case"

o	NON-RECURRING COST OF DEVELOPMENT AND TOOLING	1.250	MIO $
o	DEVELOPMENT LEAD-TIME	4	YEARS
o	RATIO OF INSIDE FINANCED / TOTAL COST OF DEVELOPMENT	10	%
o	"FLY-AWAY"-COST PER AIRCRAFT	12.5	MIO $/AC
o	PRODUCTION LEAD-TIME	2	YEARS
o	PRODUCTION RATE	50	AC/YEAR
o	CURRENT DESIGN IMPROVEMENT	25	MIO $/YEAR
o	CONTINUOUS SUPPORT, MAINTENANCE OF JIGGS AND TOOLS	0.8	MIO/AC
o	RATIO OF INSIDE FINANCED / TOTAL PRODUCTION COST	10	%
o	RATE OF INTEREST FOR THE OUTSIDE FINANCED CAPITAL	10	%
o	PLANNED RETURN ON NET WORTH = IMPUTED INTEREST ON PROPRIETARY CAPITAL	10	%
o	SALES PRICE PER AIRCRAFT	25	MIO $/AC

Fig. 4

Tangible Parameters of the Cash-Flow-Modell.Typical Figures of a Hypothetical Medium-Sized Civil Transport

The "bottom line" on the economics of civil aircraft production is summarized on the diagram 5. The heavy curve is the cumulative cash-flow for a typical program that is relatively successfull in terms of sales quantities and refers to the objective of achieving a return on net worth of 10 %. Note that the scale on the bottom of the chart is in time, expressed as "years from go-ahead", rather than in units. The curve depicts the net investment position over time taking into consideration all the factors of diagram 4.

In order to demonstrate the time impact, and particularly the impact of cost of capital, the chart distinguishes between the following characteristics:

- accumulated nominal outside financed capital
- accumulated interest on the outside financed capital
- proprietary capital

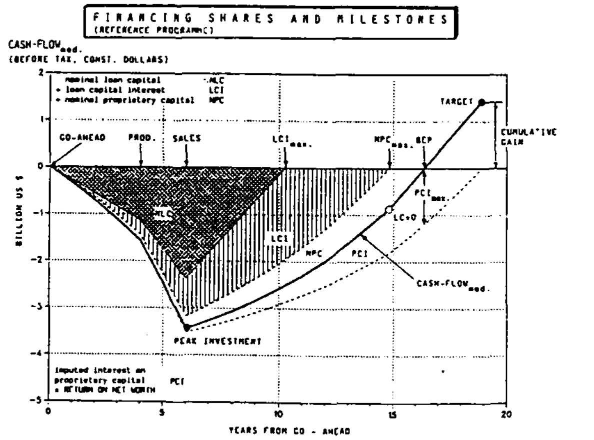


Fig. 5

Let us now discuss what happens during the years from go-ahead. During the 4-years period of development the company has nominally invested $ 1,250 million. During this time alone the cost of borrowed capital has accumulated to $ 330 million. After 4 years from go-ahead, a two-year production start-up phase joins with additional investment in inventory of $ 1,250 million without any pay-back. The nominal investment now amounts to $ 2,500 million and the cost of outside financed capital has increased within the last two years by $ 470 million and amounts to $ 800 million. Thus, six years after go-ahead, the peak-investment has accumulated to $ 3,300 million, including all financing costs. The opportunity cost, i.e. the imputed cost of proprietary capital, has reached $ 100 million.

Now, the delivery of aircraft begins. The annual program-related distribution margin is $ 560 million:

Receipts/a	50 x 25	$ 1,250 million/year
Cost	50 x 12.5 = 625	
Maintenance etc.	50 x 0,8 = 40	
Design improvement	25	
Expenditure/a		$ 690 million/year
Program Distribution Margin		$ 560 million/year

This amount is to be paid back annually to the bank or can be reinvested in other programs and can be regarded as an annuity due to a mortgage. On the other hand, the invested proprietary capital increases year by year by $ 69 million owing to the 10 percent financing proportion. After about 4 years from sales-start, or after approximately 200 aircraft sold, the nominal borrowed money has been repaid. But, at this time, the cost of outside financed capital has reached the amount of $ 2,000 million. The opportunity cost of the proprietary capital is $ 320 million. <u>In other words, 10 years after go-ahead, the total accumulated cost of capital has reached its maximum of $ 2,320 million. This equals about the total nominal investment for development, tooling and production inventory at the time of peak investment 6 years after go-ahead.</u>

14.8 years after go-ahead the loan capital including interest has been repaid. 440 aircraft had to be sold to reach this point. This, at the same time, is the point where the nominal invested proprietary capital has a maximum of $ 850 million, the imputed cost of capital is at about the same level.

Now, let us discuss the treatment of the proprietary capital invested. It can be regarded as part of the shareholders equity. Year by year, they invest money in the program and renounce the payment of interest but they expect compound interest at a rate of 10 %. Thus, 14.8 years after go-ahead their "statement of account" shows $ 1,700 million including $ 850 million crediting for 10 percent compound interest. In other words, the shareholders have outstanding claims of $ 1,700 million. The annual distribution margin of $ 560 million can be regarded as an annuity, to be paid back to the shareholders.

After an additional 1.6 years the firm's shareholders have received back the nominal invested proprietary capital. This point is called the break-even point and it is reached 16.4 years after go-ahead, or after 518 aircraft sold. At break-even, <u>all</u> capital invested in the program including capital cost owing to outside financing has been repaid but without any profit for the shareholders. At break-even the return on net worth is zero, but the imputed cost of inside financing has reached a maximum of $ 1,200 million.

The following annual distribution margin can be regarded as drawing money from the account. When the account is zero the return on net worth of 10 percent, as planned at program go-ahead, is achieved. In oder to arrive at this point in time, an additional 127 aircraft have to be sold within 2.3 years after break-even-point. In other words: <u>the objective is attained 19 years after go-ahead, 645 aircraft had to be sold with a cumulative gain of $ 1,400 million representing a 10 percent return on net worth.</u>

This analysis shows that the judgement of a long-term investment must be performed by separating inside/outside financed capital and by separating both rates of interest. There is only one figure for judging such a program, that is the compound interest on the proprietor's capital or the "RETURN ON NET WORTH". This example demonstrates the substantial impact of financing costs on the success of a long-term investment. The figures show impressively that the cost of capital very rapidly reaches the same order of magnitude as the nominal amount of money invested.

There are substantial milestones on the way to this objective:

Peak Investment

This amount is of importance in answering the question as to whether a long-term investment can be financed at all.

Zero outside Funds

This point means the end of the pay-back period of the outside-financed capital, including all cost of capital. Beyond this milestone, the annual earned distribution margins are used as repayments on the proprietary capital. At his milestone, the proprietary capital invested reaches its maximum.

Break-Even Point

All invested capital, including cost of outside financed capital, has been repaid. The cumulative imputed cost of proprietary capital, i.e. the "interest debt", relating to the shareholder's equity, has reached its maximum.

Objective

At this milestone the cumulative gain is equivalent to the planned rate of return on net worth.

4. RISK ANALYSIS

4.1 THE IMPACT OF DEVELOPMENT COST AND LEADTIME

The program cash-flow is quite sensitive, to all factors. Within the next chapter the impact of changes of parameters on milestones and on the objective is demonstrated.

A rise of the development costs (see Fig. 6,curve 1) by 10 % means an incremental investment of $ 125 million. Although the peak investment increases by the same order of magnitude, the major effects do not occur until the end of the program: the attainment of break-even requires additional 46 aircraft to be sold; the objective of a 10 percent return on net worth is achieved 70 aircraft later or 20.4 years after go-ahead (curve 1).

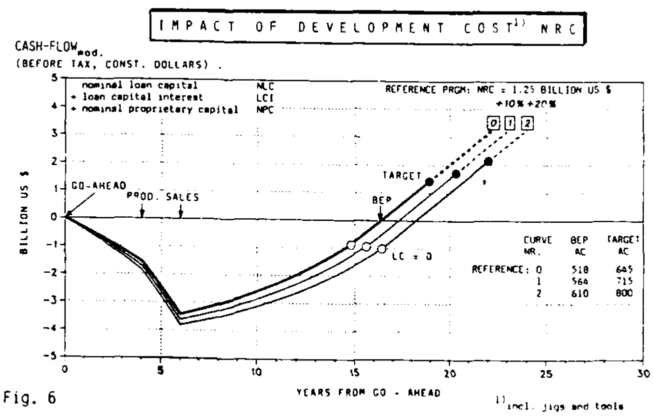


Fig. 6

Although the 10 percent increase of development costs calls for only an additional \$ 12,5 million to be financed inside within the first 4 years, the maximum invested proprietary capital heightens by \$ 100 million due to the time impact. That is the same order of magnitude as the originally planned inside financed development fund. Assuming a constant market share of 645 aircraft, the increased development costs reduce the return on net worth substantially. A 20 percent increase of development costs (curve 2) entails a reduction of the program gain down to \$ 200 million. A 25 percent increase of development costs would make the program unprofitable. Therefore, development costs must be planned and controlled very carefully.

An alteration of the development duration (see Fig. 7) entails an adequate shifting of the date of the peak investment with a slight variation of the maximum cash-flow. A reduction of 1 year causes a reduction of the peak investment of about \$ 100 million, the break-even point is lowered by 70 aircraft and the point where the planned return on net worth is obtained occurs 1.8 years earlier or after only 550 aircraft sold. Assuming a constant market potential, a development duration reduction of 1 year increases the cumulative gain from \$ 1.400 million to\$2.300 million.

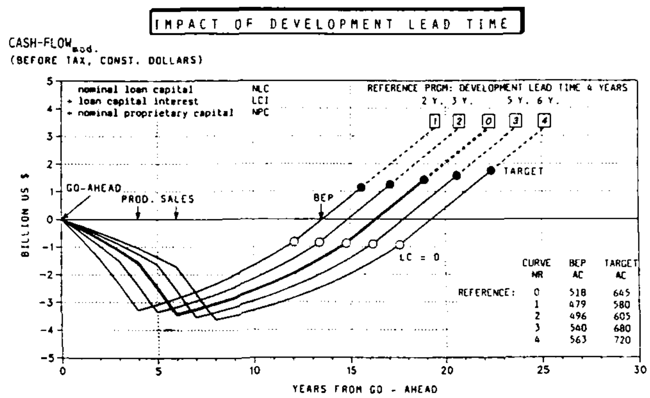


Fig. 7

The inverse is valid for an increase in the development time (curve3). Under the assumption of a constant market potential the program is jeopardized because additional 35 aircraft have to be sold only for compensation of the lead-time lag. The program gain has to be increased by about \$ 200 million in order to achieve a 10 percent return on net worth. Besides that one has to keep in mind additional opportunity cost equivalent to one annual distribution margin of \$ 560 million resulting from not realized sales within the seventh year after go-ahead.

The conclusion is that in the case of long-term investments lead-time variations - especially in early stages of a project - have a tremendous effect on the success of the project. This occurs without any change in the nominal amount of capital invested.

4.2 THE IMPACT OF OTHER PARAMETERS

A complete sensibility analysis has to take into consideration the changes of all parameters according to Fig. 4. In the following 2 examples are described: the impact of the production lead time (Fig. 8) and of the US-\$ exchange-rate (see Fig. 9)

The production lead-time of the reference case is assumed to be 2 years. The variation of this factor, as presented in the next chart, demonstrates the tremendous impact of the production lead-time on the program success.

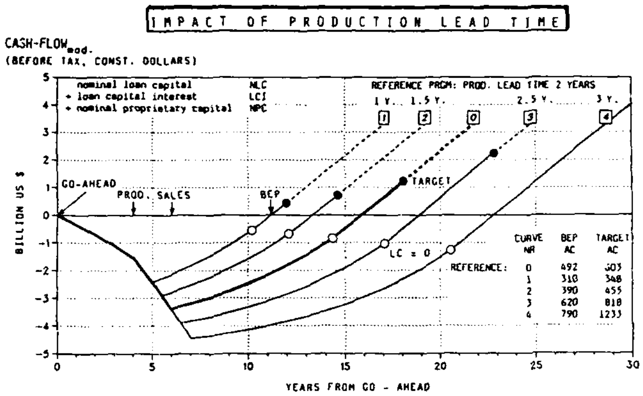


Fig. 8

Cutting down the production lead-time by 0.5 years (curve 2) has the following effects:

- Reduction of the production inventory by 25 aircraft or $ 345 million.
- Reduction of the corresponding cost of capital.
- Reduction of the cost of capital for the remaining inventory.
- These three effects sum up to a decrease of the peak investment from 3.300 million to 2,900 million.
- The pay-back period starts half a year earlier.
- Due to the reduced peak investments, the maximum necessary proprietary capital amounts to $ 650 million as opposed to $ 850 million in the reference case.
- The break-even point is achieved more than 2 years earlier, compared with the reference program and a production lead-time of 2 years.
- The program objective is reached 3 years earlier, the required number of aircraft to be sold is 455 only,in comparison with 603 aircraft. Thus, the risk of performing an unprofitable program is reduced substantially by cutting down the production lead-time.
- If the number of aircraft which can be sold remains constant, the total cumulative program gain will heighten to $ 2,600 million instead of $ 1,400 million in the reference case.

An extension of the production lead-time by 0.5 years (curve 3) produces the opposite effects. If there were only 603 aircraft to be sold on the market,- as planned on the referance case (curve 0) - the program would be terminated without any gain, neglecting the loss owing to opportunity cost.

Aircraft sales contracts are signed usually on the basis of US-Dollars. The impact of the exchange rate has to be considered in those cases where the manufacturer is producing in a country with another currency. An increased exchange rate results not only in higher revenues in the manufacturer's currency , but partly also in higher costs owing to material and equipment to be paid in US-Dollars. The following investigation assumes 30 % of the manufacturing costs to be paid in US-Dollars.

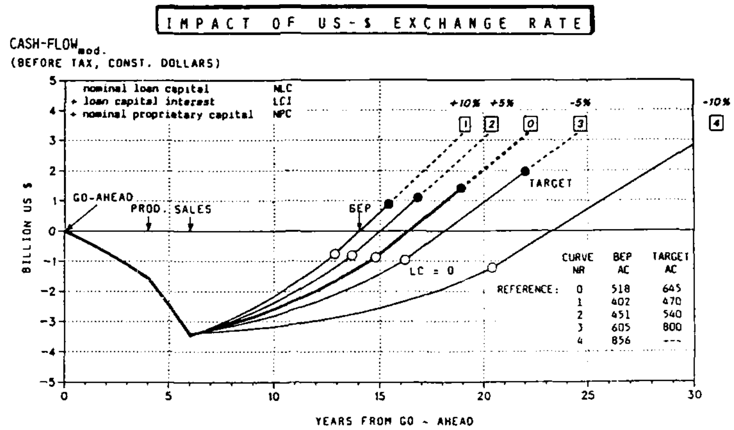


Fig. 9

A 10 percent increase in the US-Dollar exchange rate (curve 1) has the following effects:

- reduction of the maximum proprietary capital to be invested
- reduction of the "investment recovery period", i.e. the break-even point by 2.3 years or 116 less aircraft to be sold
- reduction in the total number of aircraft required to be sold by 175 in order to arrive at a 10 percent return on net worth
- assuming a constant market potential the total cumulative program gain increases from $ 1,400 to 3,200 million

Conversely, as seen from the chart, a 10 percent reduction in the exchange rate leads to an extension of the pay-back period by 7 years. The program will never attain its objective of a 10 % return on net worth because the imputed cost of proprietary capital is higher than the annual distribution margin.

5. SUMMARY

The decision to start industry development and manufacturing of a civil aircraft program should be based on sound economic principles, i.e. it should be based on quantified figures as potential economic benefits, measured in terms of conventional business criteria. An extreme example of long-term investment decision involving high complexity and risks is the aircraft industry.

The main objective of this lecture was to demonstrate a method, which distinguishes between inside and outside financed capital, and the corresponding cost of capital. Thus, in particular, the time impact is put into perspective very clearly, showing that in the case of a civil aircraft the cost of capital reaches the same order of magnitude as the nominal peak investment owing to development and production inventory. Another objective of this lecture was to discuss the impact of the major factors affecting the aircraft manufacturer's decision by performing sensibility analysis in order to estimate the risk involved in changes of the market and production conditions.

I hope, my lecture has been a contribution to an improved understanding, evaluation and judgement in the decisions we make. It is toward this understanding in the field of aircraft production that this lecture is respectifully submitted.

COMMENT FAIRE FACE A L'ACCROISSEMENT DES COUTS DE DEVELOPPEMENT

PAR
MONSIEUR CLAUDE HENOCQUE
DIRECTEUR "ESTIMATIONS ET ACTIONS SUR LES COÛTS"
S N E C M A
CENTRE DE VILLAROCHE
77550 MOISSY-CRAMAYEL

L'AMÉLIORATION CONSTANTE DES PERFORMANCES CONDUIT À UN ACCROISSEMENT NATUREL DES COÛTS DE DÉVELOPPEMENT QU'IL IMPORTE DE CORRIGER PAR DES MESURES APPROPRIÉES.

POUR CELA IL FAUT, EN PRIORITÉ, RÉDUIRE LE VOLUME ET LE COÛT UNITAIRE DES FABRICATIONS PROTOTYPES ET DES ESSAIS. CECI SIGNIFIE :

- MAÎTRISER LA CONCEPTION DE TELLE SORTE QUE LES ESSAIS DEVIENNENT DE SIMPLES VÉRIFICATIONS TECHNIQUES. CECI EST POSSIBLE GRÂCE AUX MÉTHODES ET MOYENS MODERNES DE CALCUL QUI PERMETTENT, EN OUTRE, DE MIEUX CIBLER LES ESSAIS VOIRE, À LA LIMITE, D'AUTORISER DES VALIDATIONS SUR SIMPLES DOSSIERS TECHNIQUES.

- AMÉLIORER L'EFFICACITÉ DES ESSAIS GRÂCE AUX MOYENS MODERNES DISPONIBLES ET RÉDUIRE AINSI LE NOMBRE D'HEURES À RÉALISER.

- RÉDUIRE LE COÛT UNITAIRE DES PROTOTYPES, GRÂCE À L'USAGE DE L'ANALYSE DE LA VALEUR À LA CONCEPTION, ET LA DURÉE DU DÉVELOPPEMENT GRÂCE À L'INTÉGRATION DE LA CONCEPTION ET DE LA FABRICATION ASSISTÉES PAR ORDINATEUR.

EN RÉSUMÉ, LES COÛTS DE DÉVELOPPEMENT PEUVENT ÊTRE MAÎTRISÉS GRÂCE À UNE MEILLEURE CONDUITE DES PROGRAMMES ET EN S'APPUYANT SUR LES MOYENS MODERNES DE CONCEPTION, DE PRODUCTION ET D'ESSAIS À NOTRE DISPOSITION.

SIGLES UTILISÉS DANS LE TEXTE

C.A.O. = CONCEPTION ASSISTÉE PAR ORDINATEUR
D.A.O. = DESSIN ASSISTÉ PAR ORDINATEUR
F.A.O. = FABRICATION ASSISTÉE PAR ORDINATEUR
T.G.A.O = TECHNOLOGIE DE GROUPE ASSISTÉE PAR ORDINATEUR

I/ PREAMBULE

LES EXIGENCES DU MARCHÉ EN MATIÈRE D'AMÉLIORATION DES PERFORMANCES DES MOTEURS D'AVIATION, QU'IL S'AGISSE :

- DE LA RÉDUCTION DE LA CONSOMMATION SPÉCIFIQUE,
- DE LA RECHERCHE DE RAPPORTS POUSSÉE/MASSE ACCRUS
- DE L'AUGMENTATION DE LA DURÉE DE VIE DES PIÈCES

IMPOSENT AUX DIFFÉRENTS MOTORISTES DE RECHERCHER ET DE METTRE AU POINT L'UTILISATION DE TECHNOLOGIES SANS CESSE PLUS ÉVOLUÉES, POUR FAIRE FACE À L'ACCROISSEMENT DES NIVEAUX DE CONTRAINTES ET DES TEMPÉRATURES D'ENTRÉE TURBINE QUI EN RÉSULTENT.

OR, COMME L'ONT MONTRÉ* LES CAPITAINES W.P SIMPSON ET J.R SIMS DE L'AIR FORCE INSTITUTE OF TECHNOLOGY DE WRIGHT PATTERSON, OHIO, LA TEMPÉRATURE D'ENTRÉE TURBINE EST LE PARAMÈTRE LE PLUS REPRÉSENTATIF DES COEFFICIENTS DE NIVEAUX TECHNOLOGIQUES UTILISÉS DANS LES FORMULES DE LA RAND CORPORATION, POUR L'ESTIMATION PARAMÉTRIQUE DES COÛTS DE PRODUCTION ET DE DÉVELOPPEMENT.

FAUT-IL DÈS LORS EN CONCLURE QUE LES COÛTS DE DÉVELOPPEMENT DES MOTEURS D'AVIATION PROGRESSENT AINSI, IRRÉMÉDIABLEMENT, AU MÊME RYTHME QUE L'AMÉLIORATION DES PERFORMANCES ?

IL EST CERTES IMPOSSIBLE DE NIER QUE CERTAINES COMPOSANTES DES COÛTS DE DÉVELOPPEMENT SE SONT EFFECTIVEMENT ACCRUES, CE DONT NOUS AVONS PARFAITEMENT CONSCIENCE À LA SNECMA.
NOUS ALLONS CEPENDANT VOIR QUE, GRÂCE AUX PROGRÈS RÉALISÉS PAR AILLEURS, IL EST NÉANMOINS POSSIBLE DE MAÎTRISER ET DE RÉDUIRE LE COÛT GLOBAL D'UN DÉVELOPPEMENT.

* APPLICATION OF TECHNOLOGY INDEX TO AIRCRAFT TURBINE ENGINE COST ESTIMATING RELATIONSHIP.

II/ RECHERCHE DES AXES D'ACTION POUR REDUIRE LES COUTS DE DEVELOPPEMENT

IL EST TOUJOURS POSSIBLE, GRÂCE À DES ACTIONS PONCTUELLES, D'INTERVENIR SUR LES DIFFÉRENTES SÉQUENCES DU DÉVELOPPEMENT POUR EN RÉDUIRE LE COÛT. C'EST CE QUE FONT, EN PERMANENCE, LES CADRES ET TECHNICIENS RESPONSABLES DE TOUS LES SECTEURS CONCERNÉS.

MAIS CETTE ACTION, DE TOUS LES JOURS, NE SUFFIT PAS.

MAÎTRISER LES COÛTS DE DÉVELOPPEMENT SUPPOSE, D'ABORD, DE BIEN LES CONNAÎTRE ET, ENSUITE, D'ENGAGER DES ACTIONS CONCERTÉES, POUR QUE TOUS LES PARTENAIRES INTERVIENNENT SIMULTANÉMENT, DE FAÇON COMPLÉMENTAIRE, SUR LES ORIGINES MÊME DES PRINCIPAUX COÛTS D'UN DÉVELOPPEMENT.

D'OÙ LES DEUX QUESTIONS DE BASE À SE POSER EN PRIORITÉ, À SAVOIR :

- QUELLE EST LA STRUCTURE D'UN COÛT DE DÉVELOPPEMENT ?
- QUELS SONT LES MONTANTS ASSOCIÉS AUX DIFFÉRENTES RUBRIQUES ?

SUJET DIFFICILE ET DÉLICAT, LES DONNÉES DONT NOUS DISPOSONS N'ÉTANT BIEN SOUVENT QUE LE REFLET DE RÈGLES COMPTABLES D'IMPUTATION ET DE RÉPARTITION DES FRAIS GÉNÉRAUX. RÈGLES DONT NOUS SAVONS QU'ELLES VARIENT D'UN ETAT À UN AUTRE, VOIRE ENTRE LES ENTREPRISES D'UN ETAT.

CECI ÉTANT, NOUS DISPOSONS DE DONNÉES TECHNIQUES SUFFISAMMENT PRÉCISES ET COMMUNES POUR POUVOIR CERNER LE PROBLÈME.

C'EST AINSI QUE, DANS LE CAS D'UN MOTEUR D'AVIATION, NOUS CONSTATONS QUE LES POSTES ESSAIS (PARTIELS, BANC SOL, BANC VOLANT) ET FABRICATIONS PROTOTYPES SONT ÉTROITEMENT LIÉS, BIEN QUE SOUVENT CONSIDÉRÉS SÉPARÉMENT. LA NATURE ET L'IMPORTANCE DES DIFFÉRENTS ESSAIS, OFFICIELS OU PROPRES AU MOTORISTE, ASSOCIÉES À LA DURÉE DU PROGRAMME, VOIRE AU NOMBRE DE BANCS DISPONIBLES, CONDITIONNENT EN EFFET DIRECTEMENT LE NOMBRE DE MOTEURS PROTOTYPES ET L'IMPORTANCE DES FABRICATIONS ASSOCIÉES AU DÉVELOPPEMENT.

A VOLUME D'ESSAIS DONNÉ, UN DÉVELOPPEMENT COURT NÉCESSITE LA RÉALISATION D'UN PLUS GRAND NOMBRE DE MOTEURS, ET INVERSEMENT. MAIS, POUR D'AUTRES RAISONS, UN PROGRAMME ÉTALÉ EST ÉGALEMENT GÉNÉRATEUR DE SURCOÛTS.

OR, AVEC NOS RÈGLES COMPTABLES, NOUS AVONS PU CONSTATER À LA SNECMA QUE L'ENSEMBLE DES ESSAIS ET FABRICATIONS DE DÉVELOPPEMENT REPRÉSENTE 70 % DU COÛT DE DÉVELOPPEMENT D'UN NOUVEAU MOTEUR JUSQU'À SA CERTIFICATION. IL IMPORTE DONC D'INTERVENIR EN PRIORITÉ SUR CES POSTES ET TROIS AXES D'ACTIONS PRIORITAIRES APPARAISSENT ALORS AINSI CLAIREMENT :

- RÉDUIRE LE VOLUME ET LA DURÉE DES ESSAIS
- AMÉLIORER L'EFFICACITÉ DES ESSAIS
- RÉDUIRE LE COÛT UNITAIRE DES PROTOTYPES

PLUS, BIEN SÛR, DES ACTIONS PARTICULIÈRES EN VUE DE RÉDUIRE ÉGALEMENT LE COÛT DES ÉTUDES. NOUS ALLONS REPRENDRE CES DIFFÉRENTS POINTS POUR METTRE EN ÉVIDENCE QUE DE TELLES ACTIONS SONT POSSIBLES ET BIEN ENGAGÉES.

III/VOLUME ET DUREE DES ESSAIS REDUITS

DES MUTATIONS PROGRESSIVES ET PROFONDES SONT INTERVENUES AU COURS DES DERNIÈRES DÉCENNIES DANS LE DÉROULEMENT DES ESSAIS. IL N'Y A PAS BIEN LONGTEMPS, CES ESSAIS ÉTAIENT SOUVENT DESTINÉS À VÉRIFIER DES HYPOTHÈSES, SUIVANT LES GRANDS PRINCIPES DE LA MÉTHODE EXPÉRIMENTALE, SI BIEN ÉNONCÉS PAR CLAUDE BERNARD AU SIÈCLE DERNIER. A CE STADE, L'ESSAI ÉTAIT COMPLÈTEMENT INTÉGRÉ DANS LE CYCLE DE CONCEPTION ET DE MISE AU POINT, DANS UNE APPROCHE ITÉRATIVE.

AUJOURD'HUI, GRÂCE AUX MÉTHODES DE CALCUL ET À LA PUISSANCE DES OUTILS INFORMATIQUES DONT LES MOTORISTES SE SONT DOTÉS, LES RESPONSABLES DES BUREAUX D'ÉTUDES SONT DE PLUS EN PLUS EN MESURE DE PRÉVOIR LES COMPORTEMENTS DE LA MACHINE ET SES RÉACTIONS DANS TOUT SON DOMAINE DE FONCTIONNEMENT. LES ESSAIS PRENNENT ALORS UNE TOUTE AUTRE SIGNIFICATION, PUISQU'IL S'AGIT SEULEMENT DE VÉRIFIER DES RÉSULTATS PRÉDÉTERMINÉS PAR LE CALCUL, SUR DES PARAMÈTRES BIEN IDENTIFIÉS.

A LA LIMITE, CETTE MAÎTRISE DE LA CONCEPTION AUTORISE À PRÉSENT DES VALIDATIONS SUR DOSSIERS TECHNIQUES. CECI ÉTAIT IMPOSSIBLE IL Y A QUELQUES ANNÉES SEULEMENT, SAUF À PRENDRE DES RISQUES TRÈS IMPORTANTS.

L'ESSAI DE VÉRIFICATION A AINSI REMPLACÉ CE QUE J'APPELLERAI L'"ESSAI DE CONCEPTION" CE DONT NOUS DEVONS SAVOIR TIRER PROFIT POUR GÉRER LES DÉVELOPPEMENTS SUIVANT UNE APPROCHE NOUVELLE, PLUS ÉCONOMIQUE.

UNE MULTITUDE D'EXEMPLES RÉCENTS CONCERNANT LES COMPRESSEURS, LES TURBINES, LES CHAMBRES ... PERMETTRAIT D'ILLUSTRER CETTE RÉALITÉ.

Le résultat global, pour prendre un exemple SNECMA concret et particulièrement récent, est qu'il a été possible de vérifier le comportement de la technologie du M 88 en quelques dizaines d'heures de rotation du démonstrateur et d'obtenir, en un temps réduit, une machine d'une maturité bien supérieure à celle d'un *simple démonstrateur.*

IV/ AMELIORER L'EFFICACITE DES ESSAIS

Des progrès considérables ont été réalisés dans ce sens :

- relevés automatiques de mesure
- nombre de lignes de mesure disponibles dans les bancs fortement accrus avec des capacités pouvant dépasser plus de 1000 points de mesure.

A titre d'exemple de l'efficacité de ces deux premières actions :

Il suffit d'un peu plus de 5' de rotation pour vérifier un point de performance en fonctionnement stabilisé, alors qu'au préalable 10' étaient nécessaires : 5' pour la stabilisation et 5' pour l'acquisition de la mesure. Même dans ce cas, le plus défavorable, le gain est de près de 50 % du temps.
Ce gain est bien sûr encore accru lorsque la stabilisation n'est pas nécessaire.

Parmi les autres progrès considérables réalisés, nous pouvons encore citer :

- les validations en temps réel des mesures de performances en fonctionnement stabilisé, permettant de s'assurer instantanément de l'accord entre les valeurs réalisées et les prévisions, aussi bien que de vérifier le bon fonctionnement de l'ensemble des chaînes de mesure.

  Ceci permet de poursuivre, ou d'arrêter, un essai et de confirmer, ou d'infirmer, l'intérêt d'une action technologique en connaissance de cause. Chiffrer les gains réalisés est difficile, d'autres exigences étant apparues.

  Disons simplement que ces validations en temps réel évitent d'accumuler des heures de rotation inutiles et permettent de gagner du temps dans l'avancement d'un programme.

- l'apparition de moyens de mesures nouveaux ou plus performants, permettent l'étude de phénomènes transitoires *et la réalisation de mesures instationnaires.*

  Dans ce domaine nous pouvons notamment citer les mesures par rayons X ou par balayage Laser.

Sur le dernier point, nous ne saurions trop insister sur les possibilités ainsi données aux techniciens d'appréhender des phénomènes, parfois critiques, qui leur échappaient au préalable. Grâce à ces moyens, à la SNECMA, il a été possible de mettre en évidence un déplacement parasite d'un mobile, pendant une très courte durée, avec une accélération élevée et inverse par rapport à ce que montraient des relevés trop espacés.

Tout le problème de la connaissance du passage d'un point à un autre, quand les mesures en stabilisé dont on dispose ne permettent pas d'analyser le détail de ce passage.

Cette efficacité accrue des essais permet des gains importants en délais de mise au point.
Mais elle doit surtout nous permettre de réaliser un programme d'essais avec un nombre réduit de prototypes. Sur ce point, c'est aux gestionnaires des programmes et aux Directions, de tirer les conséquences de ces progrès dans la qualité des essais et de provoquer les indispensables remises en cause de l'expérience et des habitudes.

V/ COUT UNITAIRE DES PROTOTYPES REDUIT

Au-delà de la réduction du nombre de prototypes, grâce à l'amélioration des outils de calcul et à l'efficacité accrue des essais, il est également possible de réduire le coût des fabrications.
Plusieurs moyens, complémentaires, permettent d'y parvenir :

- d'une part, la pratique de l'Analyse de la Valeur au stade de la conception, avec établissement de cahiers des charges fonctionnels et gestion du programme suivant les *principes de la Conception à Coût Objectif* (Design to Cost), permet d'aboutir à des définitions simplifiées à performances égales. La littérature prétend que des économies de plus de 25 % sont réalisables en agissant effectivement dès les phases les plus en amont de la conception, ou 15 % si le produit est à un stade de développement qui interdit certaines remises en cause.

  L'expérience de la SNECMA en matière de pratique de l'Analyse de la Valeur me permet de confirmer le bien fondé de ces données générales.

- D'AUTRE PART, IL EST SOUHAITABLE DE S'APPUYER LE PLUS TÔT POSSIBLE SUR LE PRODUCTEUR. C'EST LE MOYEN D'OBTENIR SON AVIS D'INDUSTRIEL SUR LA FAISABILITÉ DE LA CONCEPTION. MAIS C'EST AUSSI LA POSSIBILITÉ DE S'APPUYER SUR SES MOYENS DE PRODUCTION POUR RÉALISER LES FABRICATIONS DE DÉVELOPPEMENT AU COÛT LE PLUS JUSTE.LÀ ENCORE DES ÉCONOMIES DE 15 À 25 % SONT RÉALISABLES PAR RAPPORT À DES RÉALISATIONS EN ATELIERS PROTOTYPES. ENFIN, C'EST LE MOYEN DE PERMETTRE AU PRODUCTEUR DE FAIRE SON APPRENTISSAGE PENDANT LE DÉVELOPPEMENT, ET DE RÉALISER ENSUITE LA SÉRIE À DES COÛTS COMPÉTITIFS.

CETTE PRATIQUE DE L'ANALYSE DE LA VALEUR ET L'INTÉGRATION DES ÉQUIPES CONCEPTION ET PRODUCTION RELÈVENT DE CHANGEMENTS IMPORTANTS D'ÉTAT D'ESPRIT ET D'ORGANISATION, MAIS LES ÉCONOMIES À EN ATTENDRE SONT SUFFISAMMENT IMPORTANTES POUR QUE LES ACTIONS EN CE SENS SOIENT RENFORCÉES.

VI/ L'INTEGRATION DE LA CONCEPTION ET DE LA FABRICATION ASSISTEES PAR ORDINATEUR

LES PROGRÈS RÉALISÉS DANS CES DEUX DOMAINES DE LA CONCEPTION ET DE LA FABRICATION ASSISTÉES PAR ORDINATEUR SONT PARTICULIÈREMENT MARQUANTS ET VONT DANS LE SENS DE LA RÉDUCTION DES COÛTS DE DÉVELOPPEMENT.

C'EST AINSI QUE LES DÉLAIS DE LIBÉRATION DES DÉFINITIONS VALABLES POUR EXÉCUTION SONT FRÉQUEMMENT RÉDUITS DE PLUS DE 50 %, OU QUE DES MODIFICATIONS PEUVENT ÊTRE INTRODUITES EN QUELQUES JOURS, ALORS QU'IL FALLAIT AU PRÉALABLE PLUS D'UN MOIS. MAIS LE PLUS IMPORTANT EST PEUT-ÊTRE LA CAPACITÉ DE DIALOGUE ENTRE CES DIFFÉRENTS OUTILS : C.A.O.-D.A.O.-F.A.O.-T.G.A.O. IL EN RÉSULTE UNE ACCÉLÉRATION SIGNIFICATIVE DES ÉTUDES ET DES MISES EN PRODUCTION, QUI PERMET AU CONCEPTEUR DE RECEVOIR BEAUCOUP PLUS RAPIDEMENT DES MATÉRIELS POUR ESSAIS, VRAIMENT CONFORMES À CE QU'IL ATTEND.
LES ÉCONOMIES SONT IMPORTANTES MAIS JE ME PERMETS, SUR CE POINT, DE RENVOYER LE LECTEUR À LA CONFÉRENCE DE D.FALCO DE AERITALIA, IT.

VII/CONCLUSION

IL EST INDISCUTABLE QUE DES MOYENS PLUS ÉLABORÉS ET PLUS COÛTEUX ONT ETE MIS EN OEUVRE PAR LES MOTORISTES, POUR MAÎTRISER LES NOUVELLES TECHNOLOGIES NÉCESSITÉES PAR L'AMÉLIORATION DES PERFORMANCES.

TOUTEFOIS, CETTE AUGMENTATION DU COÛT DE CERTAINS ÉLÉMENTS DÉTERMINANTS D'UN DÉVELOPPEMENT MOTEUR DOIT ET PEUT ÊTRE COMPENSÉE PAR UNE MEILLEURE CONDUITE DU PROGRAMME. LES MÉTHODES ET MOYENS MODERNES DE CALCUL, LES PROGRÈS RÉALISÉS AU NIVEAU DU DÉROULEMENT ET DE L'EXPLOITATION DES ESSAIS, LES MÉTHODES D'ANALYSE DE LA VALEUR APPLIQUÉES À LA CONCEPTION, LES APPORTS DE L'INFORMATIQUE DANS LA CONCEPTION ET LA FABRICATION AINSI QUE DANS L'AMÉLIORATION DU DIALOGUE ENTRE LES BUREAUX D'ÉTUDES ET LES PRODUCTEURS LE PERMETTENT.

IL IMPORTE CEPENDANT DE CHANGER LES HABITUDES ET DE PROVOQUER LES REMISES EN CAUSE QU'IMPOSE L'EXPLOITATION RATIONNELLE DES OUTILS MODERNES À NOTRE DISPOSITION. MAIS, EN DÉFINITIVE, L'ACCROISSEMENT DES COÛTS DE DÉVELOPPEMENT DES MOTEURS D'AVIATION N'EST ABSOLUMENT PAS UNE FATALITÉ, COMME NOUS EN SOMMES PERSUADÉS À LA SNECMA.

DEVELOPMENT COST REDUCTION USING INTEGRATED CAE-CAD-CAM TECHNIQUES

by

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ABSTRACT

The conventional process of a new aircraft design and development is based on sequential analysis and test cycles.
Using an integrated CAE-CAD-CAM technique it is possible to increase the depth of the different configurations analysis, to reduce the cycle time and even the number of cycles required, and to achieve optimised design, thereby improving the product, shortening the overall development time, and reducing development costs.
The capability of CAD systems to manipulate 3-D geometric models utilizing data base of standard components, allows the integrated development of aerodynamic and structural configurations, and of systems layout.
A computerised mock-up developed at CAD allows to converge on a unique mathematical model different disciplines, making easier integrations between structures and equipments.
The CAD total data base integrated with analysis and manufacturing permits direct data transfer from engineering to manufacturing (CAM) and in addition makes faster and cheaper the embodiment of modifications during the development phase.

INTRODUCTION

The international market requirements for the defence products are related to an increasingly demanding performance in terms of mission capability and system reliability.
This leads to very complex products with higher unit costs and extended development time.
Typical peculiarities of the aircraft industry are:

- realization of weapon systems which integrate the most advanced technologies in aerodynamics, structures, avionics and armament;
- production of a limited number of units with reference to other commercial enterprises;
- relevant application of high skilled resources in a development process which takes a long time space;
- outstanding ratio of the development to the production cost;
- increasing demand on the reliability, maintainability aspects to lowering the life cost.

These requirements lead to an increasing flow-time from the definition to the initial operational clearance and to a changing between the engineering and production efforts.
The typical flow-time for a new combat aircraft development is about ten years, four of which are required to attain the first flight of the prototype.
The corresponding development cost may be split in 50% for equipment's procurement, 35% for engineering and the remaining 15% for manufacturing.

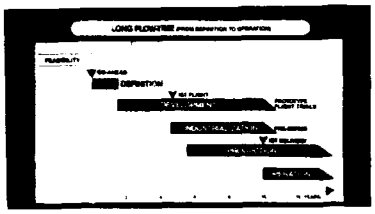

Fig. 1

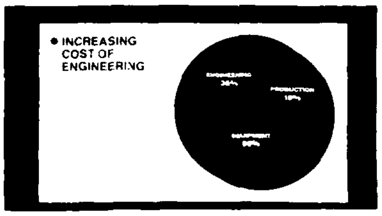

Fig. 2

Looking at past programmes, the trend of the development cost shows a very high slope due to the increased sophistication of the product.
The strategy to reverse this trend is to give particular emphasis to the engineering area, developing new methodologies with a large use of computers for the analysis and design and to keep a tight and continuous relationship between engineering and manufacturing, through a common data base.

COST REDUCTION ANALYSIS

The conventional process of a new aircraft design and development is based on sequential analysis and test cycles, which lead to its definition, design, construction and qualification.
This process offers two lines of improvement: to speed-up each cycle and to deepen the analysis, which reduced the number of cycles required to achieve systems and aircraft design able to meet the target.
Following these lines I present some applications on relevant aircraft programmes developed with Aeritalia collaboration or primary responsability, ranging from Tornado, through AMX and EAP, to the new emerging EFA.

Fig. 3

THE IMPACT OF CAE

A large use of numerical simulations, since the very initial programme phases, makes available a base of mathemtical models and informations, easing the transition to the development phase, which may be run on an updating of the data base already designed, allowing a significant time and cost reduction.
The mathematical model becomes the reference tool for each disciplines (aerodynamics, structure, loads, flutter) for the interpretation, by a process of matching and for the estimate of all the flight and working conditions.
An example of this approach is shown in Fig. 4 where the process of flutter design and qualification is described with the identification of the most relevant development cycles.

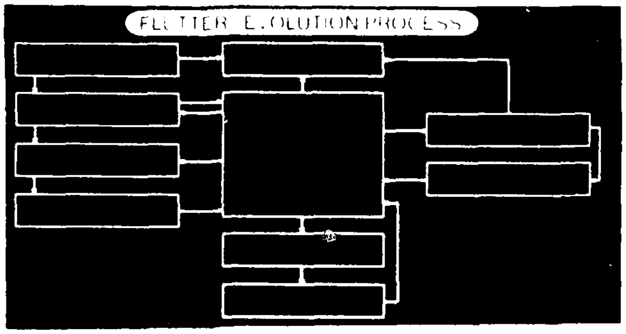

Fig. 4

Moreover the availability of computerised data base and mathematical model is used to rationalise the process of data transfer among various disciplines (i.e. aerodinamics with loads, performance, flight mechanics) and, more important, to mechanise a process of design optimisation at the computer, as for example in the area of structure design (Figg. 5-6).

STRUCTURAL OPTIMIZATION – THE CONVENTIONAL APPROACH

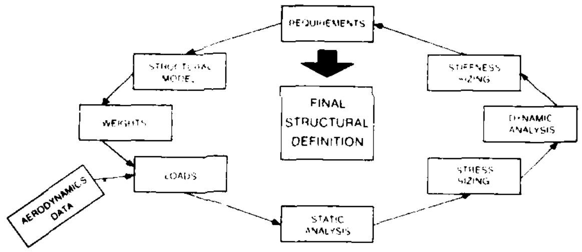

Fig. 5

STRUCTURAL OPTIMIZATION – THE INTEGRATED APPROACH

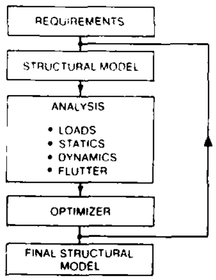

Fig. 6

All these new development methodologies result in an increase of the computer cost which is largely compensated by a reduction in man hours cost.
A balance of the two trends is not easy to be done because it is difficult to find a common reference of content between a previous programme with a new one developed with new methodologies.
We have registered that in the AMX development, the computer cost has reached a figure of 5% of the total cost, against a value of 3% in Tornado.
If we reduce the engineering man-hours of the Tornado to the value of AMX, trough parametric cost analysis, and we compare the corresponding engineering man-hours of AMX, we can identify a reduction in the range of 15% in the last programme, equivalent, to a decrease of 10% in the development cost.
In the EFA programme tne cost estimates demonstrate a more marked improvement.
In fact the cost of computer tools, in the development phase, will reach a 10% with a corresponding reduction of man-hours of 20%, within the AIT workshare.
A more dramatic impression can be made by the Fig. 7 depicting one of the most important aspect turning up in the present and future generation combat aircraft: the software content.

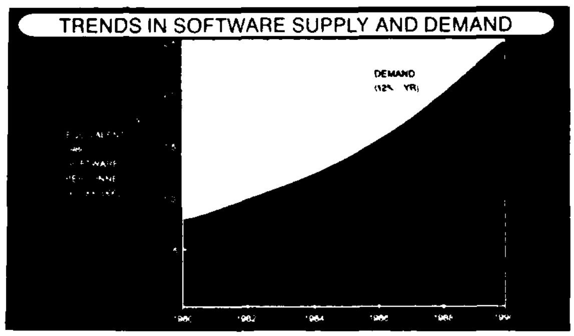

Fig. 7

Said figure underlines that in front of an exponential increase of the on board software content, the cost of its development and qualification may be reduced owing to the newly available software tools.
As an example, the software productivity, in terms of code line written for man-year, has increased by a factor of 35 from Tornado to EAP using a chain of tools called CORE-PERSPECTIVE, whose development was started by BAe.
Anyhow all above figures are very difficult to be considered as absolute values because it is not completely correct to compare different projects with different technologies, just using a parametric approach.
In any case, it is very important the fact that, basically, a large use of simulation methods, in the development phase, allows the engineers to reach a higher level of confidence in the applied solutions.

COST REDUCTION DUE TO CAD/CAM TECHNIQUE

In the area of design, the application of CAD/CAM methodologies yield a significative improvement in the cost reduction for a new aircraft.
First of all, we have to make a distinction between two basic different approaches in the use of CAD/CAM.
The first approach is the use of a CAD/CAM system as a simple replacement of the drafting table with a graphic terminal. This means usirg the CAD just for drafting and the product is a 2-D drawing.
In this case the productivity improvement may be high in the drafting area, but the overall cost reduction is affected only by the percentage of this activity, because the manufacturing area is not significantely effected.
The second approach is the use of the CAD/CAM methodology as an innovative tool to generate 3-D models of the parts.

With this approach the major benefit is the direct utilisation of the mathematical models in the manufacturing engineering, while the drawings are obtained as a simple extraction.
In order to demonstrate the cost improvement with CAD/CAM we can use a simple equation

$$C = (1 - F) + F/P$$

where C is a cost correction factor, F is the fraction of an activity which may be done by CAD/CAM, and P is the productivity improvement factor related to said activity.
As an example of what, in the Aeritalia experience, can be the cost reductions in the different categories we have this table:

COST CATEGORY	FRACTION INFLUENCED (F)	PRODUCTIVITY IMPROVEMENT (P)	COST CORRECTION (C)
DRAFTING	0.4 (40% of drawings generated by CAD)	2.5 (150% more productive)	$C = (1 - 0.40) + \frac{0.40}{2.5} = 0.76$
DESIGN	0.25 (25% of design generated by CAD)	3.0 (200% more productive)	$C = (1 - 0.25) + \frac{0.25}{3.0} = 0.83$
DATA MANUALS	0.35 (35% of data is manuals generated by CAD)	2.0 (100% more productive)	$C = (1 - 0.35) + \frac{0.35}{2.0} = 0.83$
MANUFACTURING ENGINEERING	0.60 (60% of production benefits from CAM)	3.0 (200% more productive)	$C = (1 - 0.60) + \frac{0.60}{3.0} = 0.60$

More in detail, an interesting example of productivity factor can be optained from a sample of structural parts design in the AMX programme.
To produce 472 drawings, using conventional drafting table, we needed 70500 man/hours, and for 102 drawings, produced with CAD, 7500 man/hours.
With a simple proportion, in this example, we obtain an average productivity factor of 2:1 for CAD methodologies.
It is interesting to see the relative productivity depending on the typology of the structure components represented by the drawings:

Component Typology	No. of drawings	Total Man/hours	Man/h for drawings
Carbon fiber	8	3200	400
Metal sheet	80	3200	40
Machined parts	12	720	60
Casting parts	2	380	190
Total	102	7500	73.5

The figures related to the carbon fiber parts are not comparable with conventional methodologies for two main reasons.
First, we have not produced manual drawings, because this composite structure technology has been developed in parallel to the CAD/CAM technique.

Second reason arise from the fact that the product of a 3D - CAD model requires a simple read of data for the fabrication, when the information into a conventional drawing need to be interpreted by the people of the production area. This conceptual difference makes one of the most interesting advantage of a CAD/CAM modellisation: in a CAD model we have the complete geometrical description of the parts with the corresponding plies development and the forming tools for manufacturing.
In the case of machined parts the productivity of CAD/CAM against conventional one is more easy to be evaluated, also if the number of these parts in the modern fighters tends to decrease, but in the same time the geometry comes more and more complex and difficult to define with 2-D conventional drawings.
The major measurable benefits have been obtained in metal sheet parts where the integration between engineering and manufacturing with use of automated cutting machine produce a reduction of costs at least of a factor of three due to the synergy between different people.
From our experience, finally, we see, as bigger advantage of CAD/CAM systems, the capability of solving difficult and complex shapes related to the use of emerging technologies and materials.
As I mentioned above, the carbon fiber is a good example.
The use of this material (particularly unidirectional carbon fiber tapes) has changed also the approach followed in designing the parts.
The configuration of carbon fiber composite components depends strongly on the possibilities of realisation in the shop.
Therefore this kind of structures has to be conceived by the design engineers with the continuous contribution of the manufacturing engineers.
Going toward a massive production of complex composite structures it is necessary to convert their production from manual plies lay-down to an automatic taping machining, at least of some major components.
The taping capability of these machines is limited by a number of physical factors which must be taken into account in the design, adding compromise to the optimum stress-stifness-weight design.
By the adoption of an integrated CAD/CAM system the appropriate technology factors may be easily incorporated, leading eventually to the almost automatic generation of a software which will drive the NC taping machine.
The resulting computer aided design process, which integrates design and manufacturing engineering, give an additional benefit to the cost/effectiveness of the composite structures, which are important not only for the weight reduction they allow, but also for the cost reduction, some 10-20% which are achievable versus the equivalent metal structures.

CAE/CAD/CAM SYNERGY

The engineering activity takes the most benefits with the synergy of the use of integrated CAE/CAD/CAM techniques where the different users can works together using directly a common data base.
The design of a new aircraft can reach the higher productivity (and cost reduction) if the 3-D models, generated by a CAD system, can be used both for analysis, structural design and equipment installation with volume optimisation.
An overview of the different applications which we have developed starting from initial mathematical models on data bases is shown in Figg. 8-11.
The aircraft mathematical lines are used not only for lofting but also for aerodynamics analysis or structural modelling and, finally for the parts definition.

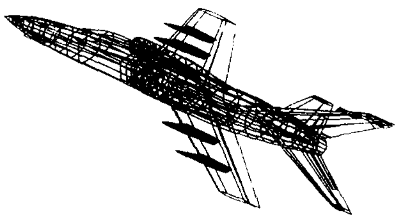

Fig. 8

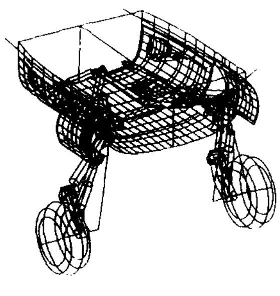

Fig. 9

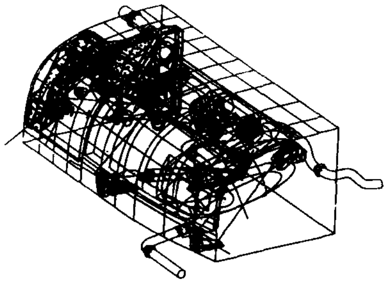

Fig. 10

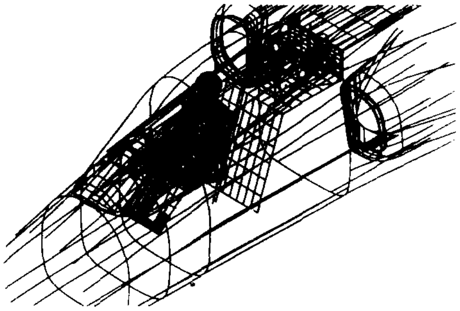

Fig. 11

What I want to examine here more in depth is the capability of mathematical modelling the different elements, (structure, equipment, routing...), which have to be integrated in an inner bay of the aircraft, allowing to locate them through the CAD technique in the most appropriate manner not only to meet the functional requirement, but also to optimize internal space utilisation.
This tecnique, already in use by the more advanced aircraft manufactures, is based on the concept of dividing the airplane body in bays.
In each bay it is possible to concentrate efforts for the integration of structures and equipments in order to maximize the benefits of a 3-D CAD system, deriving data directly for the manufacturing.
The advantages of this methodology are:

- better use of the available space
- drastical reduction of modifications in the structural parts deriving from equipments, pipings and harness installation difficulties
- faster introduction of the remaining modifications and changes
- reduction or even avoidance of physical mock-ups
- better configuration control
- more complete and precise informations for manufacturing
- improved productivity for tooling and manufacturing
- availability of perspective drawings for documentation handbooks.

A first example of this approach has been applied in Aeritalia in the AMX programme.
To demonstrate the feasibility and the cost reduction, it was selected the upper center fuselage.

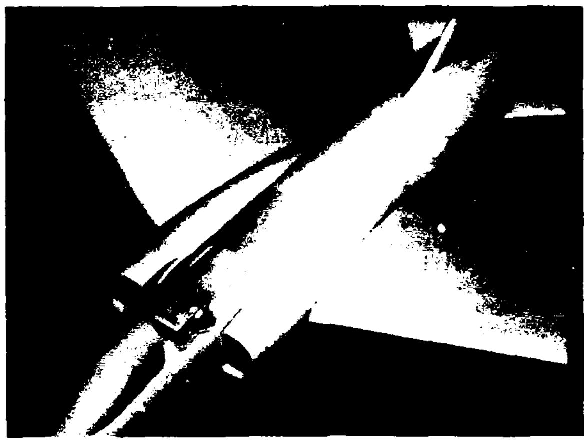

Fig. 12

The "electronic mock-up" of this bay avoided the necessity of manufacturing the physical mock-up.
With the use of the CAD system it has been optimized the available space, fitting in the structure all the equipments with its relevant pipings and harnesses connection (Figg. 13-14).

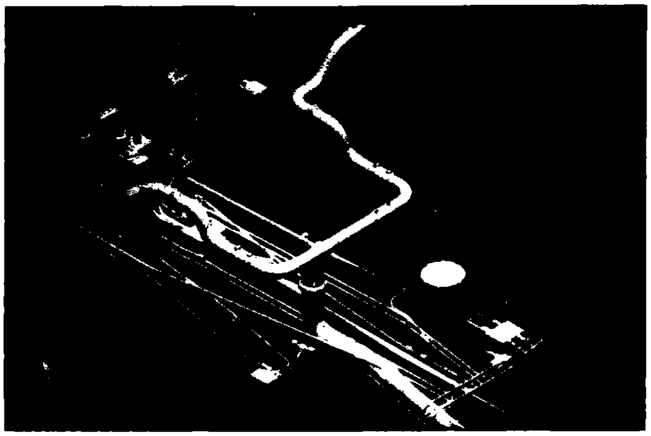

Fig. 13

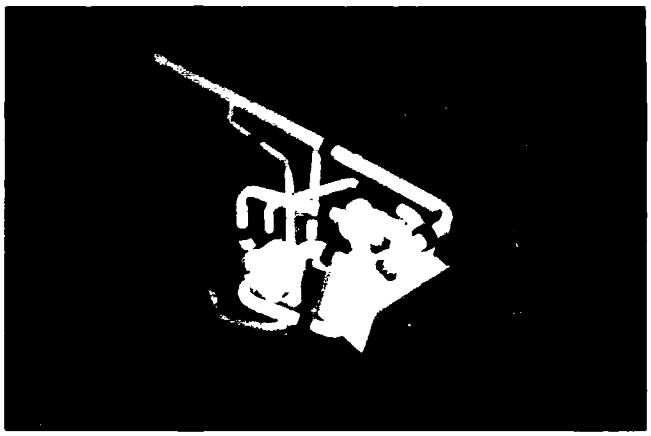

Fig. 14

From the mathematical model of the pipes it was directly derived the path for a bending N/C machine.
In the mean time the harness information, linked to the wiring diagram data base, provided all the information to the manufacturing related to the lenght, wires name, connectors, clamps and retainers installation.
The initial work to define the library of all the standards components takes about two man/years (now we have about 10.000 components in the library).
After this initial software development now it is only needed by the engineer to say to the computer the standard he will utilize, the pipe diameter and to define the path of the single pipe. Automatically the system takes all the components (flanges, collars, o-rings, etc.) from the data base (inserting it in the proper position taking into account the relevant thickness and dimension.
Having the ability to control from this mathematical model automatically the interferences between the different components, it is possible to optimise the volume utilisation and to improve the quality of the final product.

The saving, in the above presented example, was in term of engineering man/hours of about the 30% against the conventional methodology. Moreover, avoiding the phisical mock-up construction, it was saved an additional 5000 work/hours in the manufacturing.

CONCLUSIONS

Computing is now seen as the fundamental tool to link the chain design-production engineering-fabrication.
Aeritalia experience, also if it is far from a complete integration and optimisation, demonstrates the potentiality of the CAE/CAD/CAM integration in terms of cost reduction and quality improvement mainly in the development phase.
It is in fact in this phase that we have the major efforts and costs in the engineering area to delivery in time good and consistant information to manufacturing for the prototype.
In conclusion it is important to recall the fact that the emerging technologies and the use of new materials (such advanced composites, ceramics) require to develop new processes and methods of fabrication.
Therefore a large use of automation in the manufacturing area, requires new types of informations from the engineering side.
It is obvious that a robot cannot be driven by conventional drawings information.
Most of the manufacturing automation benefits can be achieved only if the engineers are able to produce the relevant and appropriate information.
To achieve this goal it is necessary to improve the sinergy between the design-production engineering and fabrication. The CAE/CAD/CAM tecnique is the main tool for this optimisation.

OPTIMIZING POWERPLANT DESIGN AND DEVELOPMENT CYCLES

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Summary

It is clear that the cost of engine development programs has been increasing over the years. The time required to complete these programs has also increased, but this is not so clear - nor so dramatic - because the added time has been placed at the front end - with R&D and demonstrator programs. Since these tend to reduce the risk of Full Scale Developments our assessment is that the total time required for engine development has not increased significantly.

While we are not at all certain that the increasing cost trend can be reversed - or even slowed down - we have described our views as to the cause and made recommendations to control the trend.

Also identified are alternatives. In this regard the derivative engine approach is cited as having strong potential for significant reductions in both time and cost. It must therefore be carefully reviewed against the "must have" (rather than the "nice-to-do") requirements of future programs.

Introduction

History shows that the development of engines has become more and more complicated, resulting in increased development requirements and cost. For example, the 1500 shaft horsepower (SHP) T700 engine development and qualification program, which was initiated in 1972, required 4 years and $290M (FY85) to complete (Figure 1). The T800 program which was initiated in 1985 will take 5 years to qualification and require

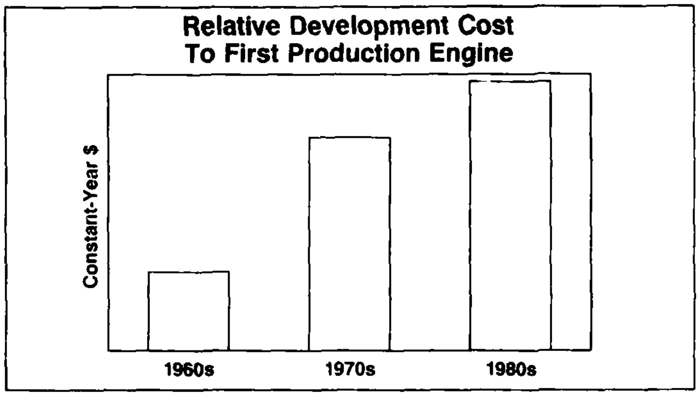

Figure 1. Increasing Cost Trend For Engine Development - 1960s Through The 1980s

some $365M (FY85) to complete. That's an increase of 20% in time and 27% in cost. This trend, which is clear, can only be controlled by a cooperative government-industry approach because, in general, governments set requirements for both military and civil engines while industry executes programs to achieve those requirements. Whether or not the trend can be reversed is, frankly, open to speculation and depends partly upon the innovation and realism with which both parties approach the issue.

The prime drivers in determining the duration and cost of any engine development program are:

1. The leap forward in technology.
2. The requirements placed on the engine for performance - not only the traditional measures such as power level, weight and fuel consumption, but the emerging and important new measures such as cost and those associated with safety, reliability, maintainability, logistics support, and "observables".

3. Procurer defined requirements on how to run the program i.e. specifies materials, number of hours required, details of specific tests, etc. rather than the results required for successful completion.

4. Generalization of requirements for multi-purposes rather than for the specific purpose intended.

All of these elements - and others - play key roles in defining the design content, number of engines required and the type and quantity of program test hours necessary to demonstrate requirements. From a practical standpoint it is these latter factors which set the time and cost necessary to achieve qualification. But they result from those items presented above.

There are, however, some bright spots in evolving management and program techniques and some lessons learned which can benefit both the timing and cost aspects of engine development. The balance of this paper is aimed at reviewing these.

The Initial Requirement Must Be Right

It's easy to recognize and seems fundamental, that changes in midstream have a disproportionately high effect on the resources required for a development program. They result in added engineering effort, less than fully useful test results and useless hardware. Yet it happens. History brings us some examples (Figure 2).

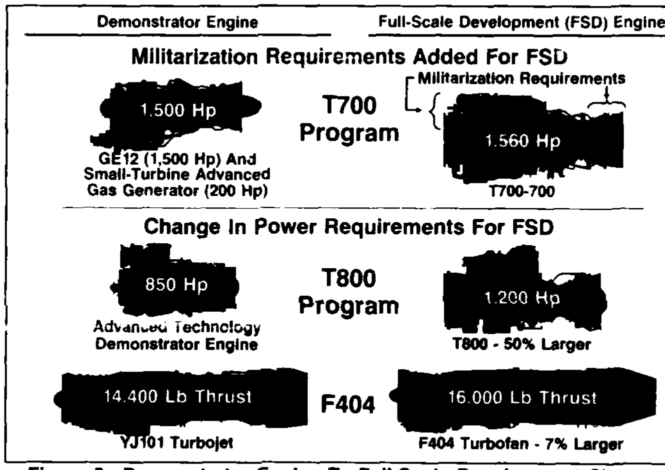

Figure 2. Demonstrator Engine To Full-Scale Development Changes

The GE12 engine - which was the demonstrator for the T700 - was defined as a performance and technology demonstrator and, therefore, did not initially address military field requirements later placed on the production engine. Incorporation of these requirements at the onset of T700 Full Scale Development (FSD) led to a power loss when the first engine was put to test. This meant that instead of a smooth flowing program from demonstrator to FSD, a large effort had to be directed at solving this problem prior to proceeding further.

The Advanced Technology Demonstrator Engine (ATDE) engine which was to be the forerunner of the LHX or T800 engine was sized at 850 SHP. But the full scale development program called for a 1200 SHP class engine. Even though scaling up is less risky than scaling down, this size increase required a considerable amount of re-engineering and therefore, the FSD received less than optimum benefit from the demonstrator program.

The Small Turbine Advanced Gas Generator (STAGG) program was approximately two years old when militarization requirements were finally placed upon it. Since the gas generator design was already complete, these requirements were too late to influence the hardware being fabricated and tested. Thus the effort had to focus only on producibility so that follow-on hardware would be able to take these requirements into account. But this follow-on hardware was not what was being demonstrated.

Today's F/A-18 Hornet is another example of system growth. Conceptually it started in the 1960's as a derivative of the Northrop F-5, requiring two 10,000 pound thrust class afterburning turbojets. It was then identified in the early 1970's as the YF-17 Lightweight fighter prototype for the US Air Force at 23,000 pounds gross weight with two 14,400 pound thrust YJ101 engines, forerunners of today's F404 engines. Currently the F-18 configured for the US Navy fighter mission has a maximum take-off weight of 36,700 pounds (with a heavier airplane for an attack mission) and is powered by two 16,000 pound thrust GE F404 Turbofan engines.

All of these experiences point to the need for assessing the product engine requirements right the first time. This means that the Planners and Requirements Setters must do a thorough job of looking to the future in engine technology, realistically establishing the requirements for the air vehicles which the engines are to power - size, weight, missions, etc., etc., as well as the field requirements which the engines must satisfy in terms of maintenance concept, reliability, safety, etc. This effort involves hundreds of trade-off studies and a vision of the future, so it is not easy - especially when one appreciates engine development must always lead aircraft development. Nevertheless, because it takes longer, it is an essential step toward minimizing the resources required for engine development. In fact, engine development should be launched only after this step has been completed in confidence and the disciplines for downstream controls of the air vehicle system are in place.

There has been, and still is, a tendency to correct problems experienced in one program or another by "blanket legislation" applied to all programs. This results in broad specification requirements which become necessary for the designers of all new products to respect. This approach tends to restrict design innovation, add unnecessary testing and add to the cost of the program. In addition, the general specifications for gas turbine engines, at least in the U.S., require "compatible" engines - engines that must be compatible with the needs of all the services and engines that can be compatible with multi-purposes. While there is some merit in this to be sure, it must be recognized that this adds to program and product cost. Again, the point is that the Planners and Requirements Setters need to do a thorough job of looking ahead to see what their real needs are and they should specify the "must haves" rather than the "nice to do's" if we are to blunt the upward trend in product development cost. In short, the tendency to "gold plate" our products has got to be resisted.

There is no question that requirements for all our products are escalating - and this is as it should be (Figure 3).

Engine Test	1970-80s	1960s
• Corrosion Susceptibility	•	
• P/T Overspeed	•	•
• GG Overspeed	•	•
• Water Ingestion	•	
• Loss Of Load	•	
• Engine Overtemperature	•	•
• Engine Overtemperature / Control System	•	
• Sand Ingestion	•	
• Smoke Emission	•	
• Altitude Performance	•	•
• Low Cycle Fatigue	•	
• Ice Ingestion	•	
• Anti-Icing	•	•
• JP4 Endurance	•	•
• JP5 Endurance	•	
• Bird Ingestion	•	
• Windmilling	•	•
• Cold And Hot Starting	•	
• Altitude	•	
• Loss Of Oil	•	
• Vibration	•	
• Electromagnetic Interference	•	

Figure 3. Qualification Comparison

New technologies bring new capabilities and we owe it to our products and our industry to see that each generation exceeds the performance of the last in those aspects important to its end use. Nevertheless, the constant crossing of new frontiers is not inexpensive and our Requirements Setters must carefully balance the impact of these with the overall benefits. While there are existing models (such as life cycle cost) for making some of the necessary trade-offs there is also a clear need for standardization of these models so that they can be consistently applied and yield agreed upon results.

A final step in getting the requirements right the first time is for the Requirements Setters, including Civil Planners, to circulate these early program drafts to those in industry who are expected to participate in product development for comment early enough so that these comments can be considered prior to formulating the final program specifications. This is important for several reasons. First, it provides an initial assessment from the "doers" of cost and technical trade-offs and this aids the planners in risk assessment. But it also allows for the insertion of alternate technology approaches to problem solving. Finally, but not the least important, it sets the stage for "buyer-seller" cooperation which is fundamental to the successful completion of the program which is to be accomplished later. It is a pleasure to report that this approach is being used with increasing frequency today.

Risk Eliminators

Risk eliminators are also cost reducers because they provide the means of identifying achievable technical goals prior to and sometimes during a full scale development. R&D programs for component and process development, models and simulations, and demonstrator programs all have the advantage of proving concepts in small dedicated programs prior to committing oneself to full development programs.

In the engine business a normal development sequence (Figure 4) has evolved. This begins with model

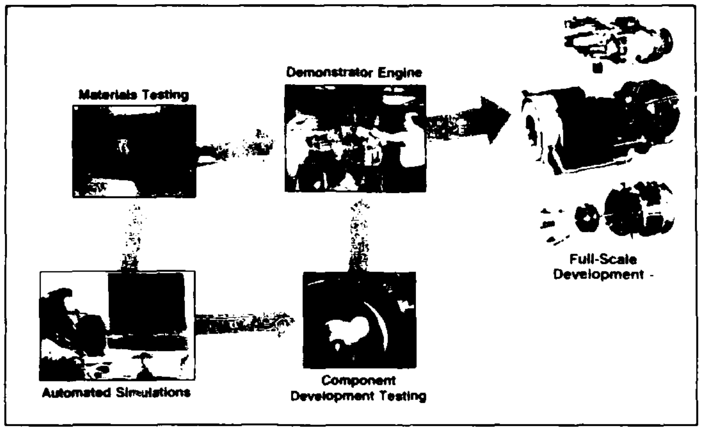

Figure 4. Typical Stages Of An Engine Development Effort

simulations which continue to take advantage of skyrocketing computer technologies, then proceed to component and process research and concludes with demonstrator engines has evolved. All these take place prior to the commitment of full scale resources and with lesser time constraints. Because our business and our products are so technically complex and full scale developments are so expensive, this risk reduction approach is essential when the technology leap forward justifies it. Still we must hone the approach to better fall in line with future requirements as discussed earlier.

Government programmers have recognized the necessity of this sequential phasing and have aligned their funding categories to permit its execution.

Executing the Development

Our experience and success at General Electric with our T700, F404 and F110 engines in recent years has resulted in some lessons learned to be applied to approaching and executing the full scale development. The following paragraphs summarize these.

o A careful assessment of the requirements in order to understand the priorities, payoffs, and interrelationships, along with an equally careful assessment of the technology to be applied. We thoroughly scrutinize our research and demonstrator experiences with other engines for the application of those technologies suited to the program at hand. When full scale development is launched we are looking for the "previously proven" in scales that can be easily applied. The commitment of resources is too large to be dealing with fundamental research in a development program.

o Organizing for the task at hand. Small, dedicated and co-located teams consisting of all the necessary disciplines provide the talents, communication and espirit de corps necessary for success. We know that we must inject all the requirements at the piece-part level before we get started. This includes performance, test, reliability, maintainability, safety, airframe integration, producibility, cost, timing, and all the rest. So we need the specialists working at close range with the designer in order to trade off, iterate, agree and approve designs as they emerge.

o Program definition. The most significant task in this regard is the definition of the test program because this determines the test hours and number of engines required which play so heavily on the cost. It is absolutely essential from a cost and timing standpoint to get the instrumentation plan down right. Over-instrumentation costs money but under-instrumentation does the same because it complicates problem resolution, requirement substantiation and product definition. The role of each engine must be maximized and the important tests must be put up front. Well integrated orchestration of the test flow leads to the most productive use of each nameplate. Hardware flow needs to be carefully synchronized with test

results. The hardware task, in simple terms, is to get critical hardware through component and initial engine testing early enough to provide design confidence prior to the commitment of large quantities. One key is flexibility for critical hardware. For example, the long lead castings and forgings need to be defined early but the machining cycle has to be phased to early test results. The same applies to tooling where the objective is to tool once and avoid iterations made necessary by design changes.

o Test Program. In general testing can be divided into classes of investigatory and proof, safety, environmental and endurance testing. The bulk of the test hours are devoted to the latter category and this is an area where we believe efficiency improvements can be obtained. Our experience at GE with Accelerated Mission Testing (AMT) has been outstanding. We believe it provides a superb opportunity for proving the durability, maturing the design and meeting the qualification requirements with better results and at less cost than current methodology produces. The AMT cycle is constructed from a mix of the various missions which the intended aircraft will fly during its service life (Figure 5). In order to identify the power settings at which the engine is to operate during the AMT the ambient conditions - altitude and temperature - at which the air vehicle will operate is determined (Figure 6) along with the percentage of the vehicle's life to be spent at each of these. Finally, engine deterioration characteristics are applied (Figure 7) and these, along with the ambient conditions, set the power levels for the engine. The result is a test cycle (Figure 8) that accounts for the important engine life-determining factors - time at maximum power (TAMP), equivalent low cycle fatigue cycles (ELCF) and equivalent full thermal cycles (EFTC) so that all of these can be proven in a single test - and proven to better standards, in our opinion, than currently required tests. This is so for two important reasons:

First: The AMT is run to the design life of the engine rather than an arbitrary standard of 150 or 300 hours.
Second: When done early enough in the development program it provides the basis for problem determination and correction and so it is an essential tool for attaining maturity early in the engine's life cycle.

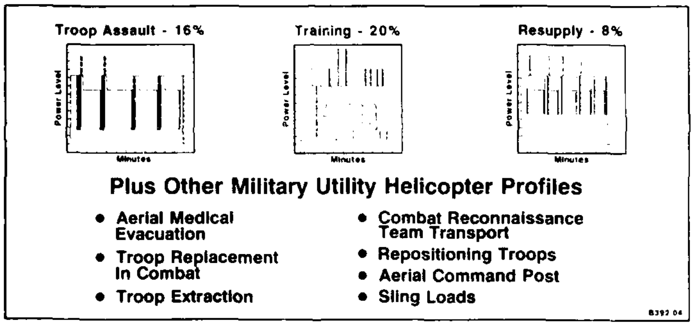

Figure 5. Mission Power Profiles Typical Of Military Utility Helicopter Operation

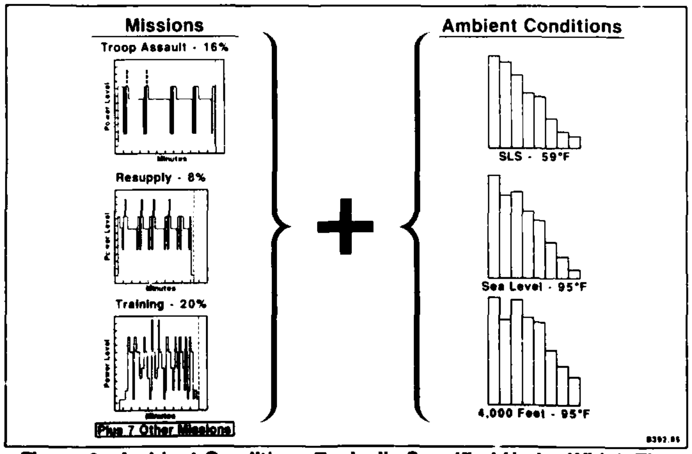

Figure 6. Ambient Conditions Typically Specified Under Which The Representative Missions Will Be Flown

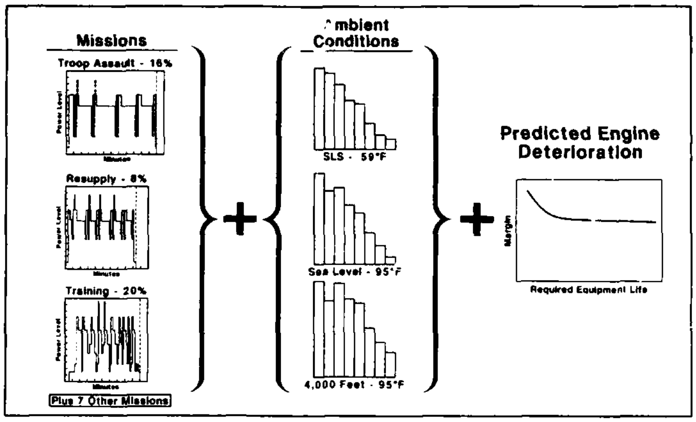

Figure 7. Predicted Product Deterioration Factors Established - And Included

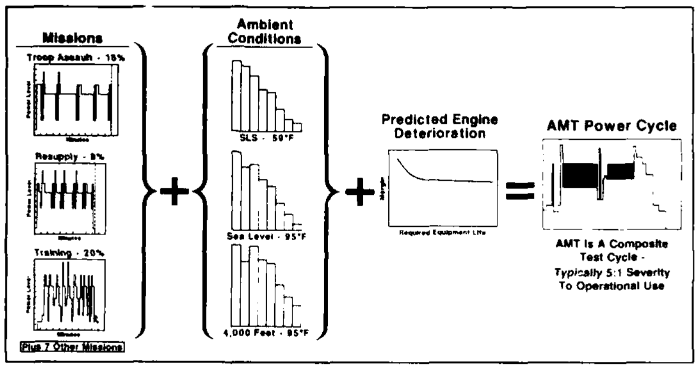

Figure 8. Construction Of The AMT Test Cycle

	Severity Factors		
	150 Hour MQT	300 Hour MQT	AMT
• ETAMP	35.6	20.1	7.08
• ELCF	0.5	1.02	4.75
• EFTC	6.4	53.3	9.95
• Spread Of Factors	71.1	197.1	2.1
• Test Hours To Demonstrate All Factors (5,000 Hours Engine Life)	10,000	4,800	1,050

Figure 9. AMT Provides Better Balances

The AMT as a standard could replace the low cycle fatigue (LCF) tests and endurance tests now required as a formal part of engine development. It lends itself to "acceleration" (Figure 9), that is, the accumulation of TAMP, ELC and EFTC's in real time much faster than by flying the actual missions because the accumulation of time at non-threatening - or low power - portions of the mission are eliminated. As a repetitive test it is also easily automated. It has the potential for reducing the number of nameplate engines since it combines the various endurance and LCF tests noted above thus eliminating the need for dedicated engines (Figure 10). All of these factors contribute to the reduction of program development time - especially development to maturity - as well as program cost. Finally, the AMT provides the basis for a much better integration of development and production tooling because it verifies the durability so much quicker. This, in turn, allows earlier concentration on producibility requirements such as hard tooling because the threat of design changes for durability reasons is eliminated early on.

Old - 150 Hour MQT	New - AMT-Oriented
• 150 Hour MQT • Low Cycle Fatigue	• 150 Hour AMT
• 1,000 Hours To MQT Cycle • Accelerated Simulated Mission Endurance Test	• 1,000 Hour AMT
• AMT	• AMT
10,000 Hours	5,000 Hours
14 Engines	8 Engines
48 Months	36-40 Months
Base Cost	0.7 Base Cost

Figure 10. Comparison Of Development Programs

Alternatives

Derivative Engines

One alternative to new engine development is the derivative engine approach. Derivatives are typically qualified in about 3/4 of the time necessary for new engine full scale development programs (Figure 11) and at something like 10-30% of the cost depending on the requirement. They also eliminate most of the research as well as the demonstrator programs which are advocated for new engines prior to full scale development. In addition, they typically result in better engines than the parent model from which they are derived (Figure 12). The derivative engine approach, therefore, must receive strong consideration as a candidate engine for new propulsion requirements to meet the needs of future air vehicles. The lower investment is an important consideration in both military and commercial use. From a military standpoint it reduces the drain on overall funding and this can be applied to overall budget reductions or to the funding of other essential programs. The shorter time cycle provides for earlier military availability - often a crucial requirement. In the commercial business the lower investment cost translates into lower costs to be recovered by the developer through sales of the product. This plus the shorter time to market place appearance tends to maximize the market. Overall, then, the derivative offers strong advantages in lower program risk, lower investment costs to be recovered, earlier availability, installation commonality with prior versions of the same model, minimal disturbance to existing logistics systems and better field performance in terms of reliability and maintainability. These advantages must be traded against the "must have" (not the "nice-to-do") requirements for advanced propulsion systems before proceeding with a new "next generation" engine.

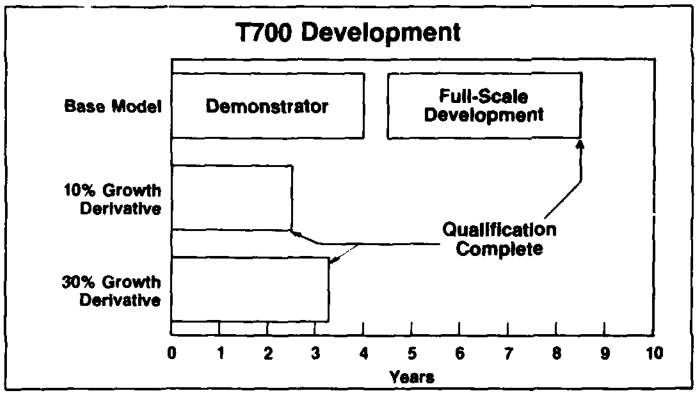

Figure 11. Development Program Time For Baseline Engine Versus Subsequent Derivative Growth Versions

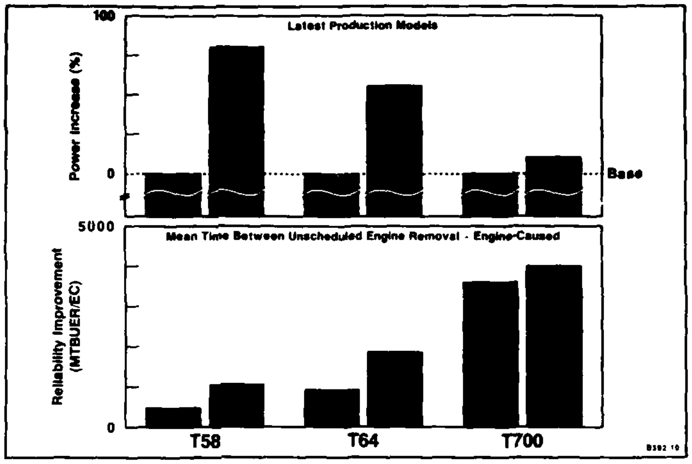

Figure 12. Historical Turboshaft Engine Growth In Power And Reliability Improvement

Partnerships

It is no secret that the cost and risk of new developments sets the stage for partnerships for engines and many other products as well. Partnerships - in their various forms of joint companies, co-developments, consortiums, revenue sharing, etc. - allow for cost and risk sharing among the various parties to the partnership and this enables the launching of certain programs which, otherwise, would not be launched. They also enhance the market for the product by combining the marketing strengths of all the parties. And they provide for the pooling of technologies which can result in a better product than would be achieved by any single partner. These are important advantages which, of course, is why there are so many partnerships. But there are disadvantages as well. There is no question regarding the fact that, although the investment of any one partner is less than in the "go-it alone" route, the total investment of all the partners is higher than if the job were to be done by one of them. Partnerships, inherently create an integration, coordination and communication requirement which is not present when the job is done by one party and this adds to the overall cost. They (also inherently) create a certain amount of duplication which good management can minimize, but not eliminate, and this also adds to overall cost. Careful management can control program timing - but the risk of program extensions is always present because of the added requirements. Notwithstanding these disadvantages we believe that partnerships are now a way of life and are here to stay.

Competition

Primarily as a method for cost control, the US Government has embarked on a strong and dedicated program to compete everything from R&D, demonstrators, development through product improvement, to production and support. The use of competition in R&D and in demonstrator programs is not new. In these phases, competitive approaches allow a range of technical alternatives and management approaches to be exploited by the customer in programs which do not demand huge resources but which do provide a basis for competing Full Scale Development Programs and which can significantly influence the future of the product. There has also been substantial activity in support competition - especially spare parts. Results seem to indicate that resulting costs could be lower although the loss of certain services typically provided by the Prime Contractor (quality surveillance and configuration management) for example are not fully evaluated.

In the product development and improvement areas it is too early to judge results since these initiatives are so new. We suspect, however, that they will result in higher costs in spite of the demonstrated willingness of companies responsible for developing products to invest in the development phase. Even with these investments, the total allocated to each of two competing developers seems higher than required for any one of them to do the same job. Since these companies are in business to make a fair return on their investments, then the investment plus the return will be recovered downstream in the sale of products and services.

Competition in production has also yet to be proven as a method for cost savings. Here the impact of multiple tooling and the potential for dual logistic systems for basically the same product seem to indicate that programs which are to be considered as candidates for competition in production must be both very large and must have at least the potential for long term production runs.

Our early tentative conclusion, therefore, is that this procurement method does not reduce development cost but, instead, increases it although it displays advantages in the R&D phase.

Recommendations

Our experience indicates to us that there are approaches available to control escalating engine development program cost and duration. These are as follows.

1. Establish clear cut goals and specifications by the Requirements Setters and Planners. This requires a "vision of the future" for both military and civil scenarios and involves hundreds of technical, economical and military trade-offs. This is much easier said than done and involves the elements of:

   a. Maintain a realistic vision of the future;

   b. Firmly define the air vehicle which the engine is expected to power including its size, weight, configuration and mission requirements or, at the very least, the range within which these aspects of the projected design can vary. These definitions must include realistic allowances for growth and margins;

   c. Establish the disciplines necessary to control the elements of b. above within the ranges layed down. This "taking the pledge" is so fundamental that results cannot be expected to be significant without it;

   d. Eliminate unnecessary requirements which calls for judicious tailoring of engine product requirements to the intended use. Focus on the "must have" rather than the "nice-to-do" and "what went wrong the last time";

   e. Carefully assess the technology to be applied. If a significant "leap forward" is to be achieved then front end time must be allocated for the Research & Development and for Demonstrators which must precede FSD in order to proceed with reasonable risks;

   f. Iterate the goals and requirements with industry as they are developed and before they are "cast in concrete".

2. Structure the total program initially to a solid set of requirements - or a range of variation in requirements. Only after these are developed can a sequential flow of R&D, Demonstrator and FSD be established and cost and timing necessary for completion be assessed.

3. Control the cost of Full Scale Development by implementing the following.

   a. Understand the requirements, their interrelationship, and impact on piece part design before the design is initiated. From the beginning lay down a design to meet all the requirements in the product engine - not a "development vehicle".

   b. Co-locate a dedicated team with all the skills and talents necessary to accomplish the program and dedicate them to this task. Establish smooth, fast and effective lines of communication among team members and other supporting personnel resources. Make certain that their "ownership" is clear.

   c. Provide early and important attention to the test program requirements with special emphasis upon instrumentation, placement of key elements up front, integration of related tests, hardware and tooling plans.

   d. Substantially increase the use of AMT including substitution of AMT for specified LCF and official Qualification tests. We believe strongly that AMT can reduce the number of nameplate engines, reduce the program duration and cost and, at the same time, produce a better product.

4. Consider the role of partnerships. Our assessment of partnerships - in the various forms - is that they reduce the "apparent" cost, that is the visible up front cost, but increase the overall cost and therefore the cost to be recovered. But they have other advantages as well. We believe they are here to stay and the key issue is to select the right form of partnership for all aspects of the program at hand.

5. Use single source procurement strategy for Full Scale Development following competitive R&D and Demonstrator phases. Dual source development increases program cost and is an unnecessary risk reducer once the proper sequential program structure is established.

6. Increase the role of derivative engines in meeting future requirements. Because derivatives cost less and take less time they need not be initiated so early and this allows the Requirements Setters and Planners a better opportunity to do their job right the first time. The derivative, while it must meet the "must have" requirements, also offers advantages in producing better engines and fitting existing logistics systems.

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AVIONICS ACQUISITION, TRENDS and FUTURE APPROACHES

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SUMMARY

This paper covers the current and future direction of U.S. Air Force avionics. While the paper discusses primarily tactical aircraft avionics, the findings and conclusions are applicable across USAF systems. The paper covers the acquisition methodology, the background history and trends of avionics and future approaches in avionics. The basic drivers for avionics are operational needs, availability, survivability, available technology, cost and schedules. The challenge is to provide effective avionics in a budget constrained world. To accomplish this requires emphasis on providing performance to counter the threat, flexibility for diverse use and basing, cost and schedule realism, and systems capable of being upgraded through planned growth as the threat changes. Care must be taken to control requirements. It has been shown that the final five to ten percent improvements in performance can increase the cost twenty to fifty percent, therefore, we should strive for "sufficient" performance not "best" performance. While initial acquisition cost is of concern, life cycle cost is even more important. To keep life cycle costs down and have an effective system during combat, maintenance concepts need serious attention. To accomplish the above objectives, the discrete avionics systems of the past must be replaced with integrated avionics responsive to crew needs, increasing threats and fiscal constraints. Future needs will cause continued increases in avionics cost. The use of new technologies, new avionics system integration and architecture techniques, use of common hardware, modular and reusable software and improving the environment in which the avionics must operate, can control the life cycle cost of avionics while meeting needs of future systems.

PREFACE

The purpose of this paper is to document and investigate the methods of avionics acquisition, past characteristics and trends to better understand the reasons for cost growths and increased schedules. In addition future approaches are investigated to determine their impact on cost and schedules. Finally some required technologies and future approaches to control avionics cost and schedules will be presented.

INTRODUCTION

Technology advances in the last two decades in analog and digital avionics have added tremendously to weapon system effectiveness. These same advances have caused the cost of the avionics in fighter aircraft to go from approximately 10% of aircraft flyaway cost to approximately 30% of aircraft flyaway cost. In addition the operating and maintainability costs have increased to the point they exceed the development and acquisition costs. The time from initial concept to initial operational capability has increased from approximately 10 years to approximately 15 years.

AVIONICS ACQUISITION/DEFINITION

The acquisition of avionics systems, like total weapon systems, is broken into five phases. These phases are "Conceptual Phase, Demonstration/Validation Phase, Full Scale Development Phase, Production Phase and Deployment Phase".

The "Conceptual Phase" is aimed at transforming operational needs into a description of required avionics functions, avionics system performance and system options. This is accomplished through an iterative process of sensitivity analysis, trade studies, technology assessments and concept evaluations. The results of this phase will provide candidate avionics approaches and will define new technology needs.

The objectives of the "Demonstration/Validation Phase" are to define the avionics, demonstrate critical technologies and prepare the development specifications. The avionic system definition consists of requirements analysis to establish required performance for the avionics functions, definition of the concept of each function, definitions of subsystem, allocation of performance and functions to subsystems, design studies, trade studies, and evaluation of standard or existing avionics equipments to meet requirements. Where high risk components, subsystems, software integration or techniques are required, the "Demonstration/Validation Phase" will include prototyping, testing and demonstration of these areas to reduce risk prior to the "Full Scale Development Phase". It should be kept in mind that this phase includes integration of reliability, maintainability, safety, survivability, and human factors into the total avionics definition and design. One other critical factor in this avionic system definition is the area of affordability; including initial acquisition cost, producibility, and operating and maintenance cost.

The "Full Scale Development Phase" consists of detailed design, development, fabrication, integration, software development, test and evaluation. This phase includes the definition and control of the interfaces within the avionics system, as well as interfaces with the airframe and other aircraft subsystems. This phase includes ground and flight testing to verify and validate avionics performance and design. In addition to the development of the avionics, all support equipment is designed and developed. This phase results in production specifications, acceptance procedures and interface control documents.

The "Production Phase" covers the fabrication and acceptance testing of avionics hardware and software. In addition, this phase accomplishes engineering changes and interface control. The preparation of operating and maintenance manuals and operational technical data.

The final phase is the "Deployment Phase". This phase consists of training, operational use and field intermediate level and depot level support of the avionics system.

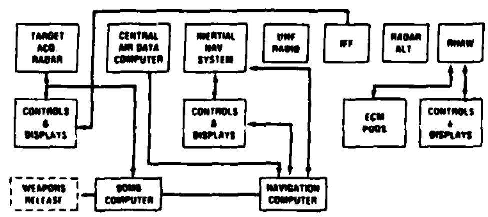
Avionics acquisition is an iterative process to transform an operational need into a delivered avionics system to satisfy the need. This is accomplished through the use of definition, synthesis, analysis, design, development, simulation, test evaluation, engineering and production. It is designed to ensure compatibility of all physical, functional and program interfaces in a manner to provide an avionic system that satisfies operational needs, and meets reliability, maintainability, safety, survivability and human factors requirements at an acceptable cost and schedule.

The drivers in the definition, development and acquisition of avionics are the operational needs, availability, survivability, available technology, cost and schedules.

AVIONICS TRENDS

The last two tactical fighter aircraft (F-15 and F-16) acquired by the USAF, have taken just over ten years from the beginning of the Concept Definition Phase to the Initial Operational Capability (IOC) date. It is estimated the next tactical fighter will require approximately fifteen years for the same efforts. The "Full Scale Development" and "Production" phases will require approximately the same time as for the F-15 and F-16 fighters (approximately seven and one/half years). The major difference is in the concept definition and demonstration/validation phases. Instead of approximately three years to accomplish these phases, it is estimated to require more than seven years. The reasons for this increase are the length of time required to make decisions, the many analyses and trade-off studies required to substantiate recommended approaches, and utilization of the latest avionics technology. This approach requires additional time to mature and demonstrate these critical technologies, during the demonstration and validation phase. Previous systems utilized existing proven technologies and implemented multi-stage improvement programs to incorporate new technologies as they became available, allowing an abbreviated demonstration/validation phase.

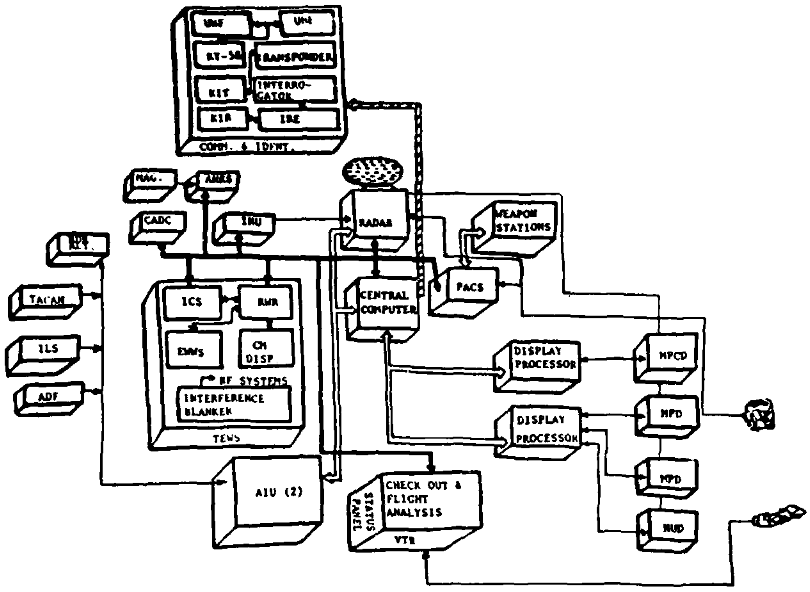
The architecture of avionics systems has changed significantly over the past twenty five years. In 1953, the avionics system for the F-100 aircraft included a range only radar, an analog computer, a sight, a navigation compass and display, a UHF radio and an identification friend or foe (IFF) system. These equipments were stand alone analog equipments and the integration of the outputs were accomplished by the pilot. This avionics system weighed 700 pounds. The avionics system for the F-4 aircraft is depicted in Figure 1. This system became operational in 1960 and weighed approximately 2500 pounds. This system integrated the search and track radar with the navigation, controls and displays using dedicated hard wired interfaces. While this system provided some computational aids the pilot using analog computers, many crew decisions and much crew integration of information was required.



F-4 AVIONICS (1960)

Figure 1

The F-15 avionics system (approximately 2000 pounds) became operational in 1975 and is depicted in Figure 2. This avionics system was the first fighter avionics system to use multiplex buses instead of point-to-point hard wiring and was a fully integrated digital avionics system. Many functions that were previously performed by the operator, were automated with crew override capability to ease the operator workload. Many new functions and capabilities were included. This system showed the advantages of multiplex buses and digital integration. This led to the development of a standard multiplex bus, a standard computer instructions set architecture, standard higher order language and standard stores interfaces which were used on the F-16 and B-1B avionics systems. The benefits of the standard multiplex bus have been in the areas of development, flight test and growth. In development the system integration was largely reduced to a software task, most changes were possible without hardware impacts, subsystem simulations were simplified and data recording and monitoring were simplified. During flight test, the use of the bus provided quick turn around and simplified data analysis. The use of the bus has allowed ready integration of new equipments for advanced capabilities. The use of higher order languages has provided coding with less errors, increased programmer efficiency, reduced programmer training, easier documentation and simplified modifications.



F-15 AVIONICS (1975)

Figure 2

Another way to look at what has happened with fighter aircraft avionics is to look at the installed weights of these systems. The weights of fighter avionics systems are shown in Figure 3. As can be seen, the weights continued to increase from the early 1950s to the late 1960s. These systems used vacuum tube and transistor technology. With the advent of micro circuit technology, this trend was reversed and the added capabilities and functions were added with less weight. It appears that the weights have at least leveled off. If the weights of the avionics systems are looked at in light of the total aircraft weight, it can be seen that the avionics contribution to total aircraft weight has also leveled out at approximately nine percent (9%). This is shown in Figure 4.

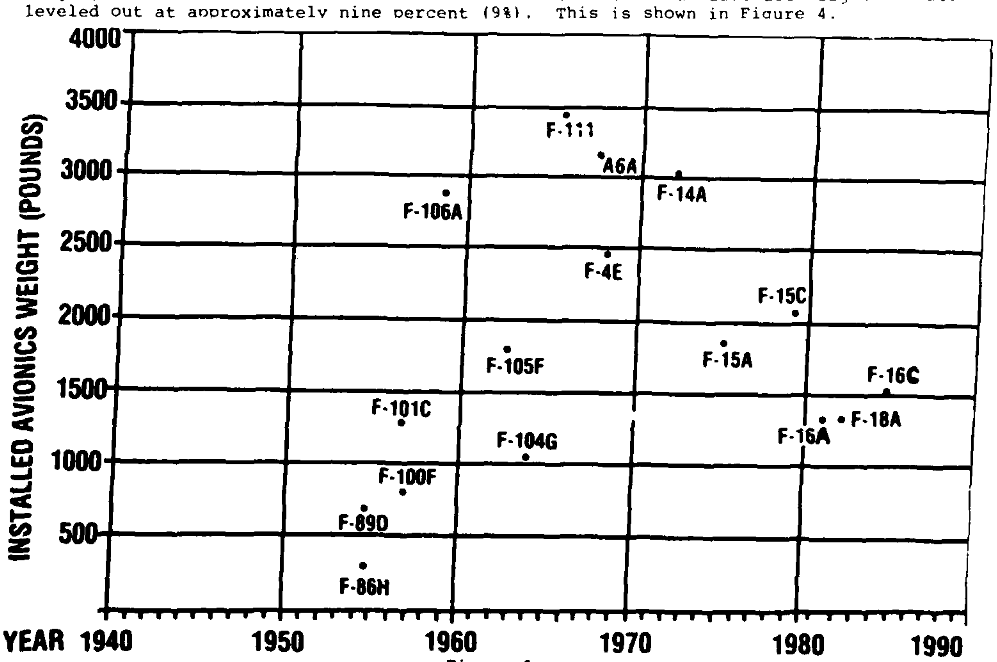


Figure 3

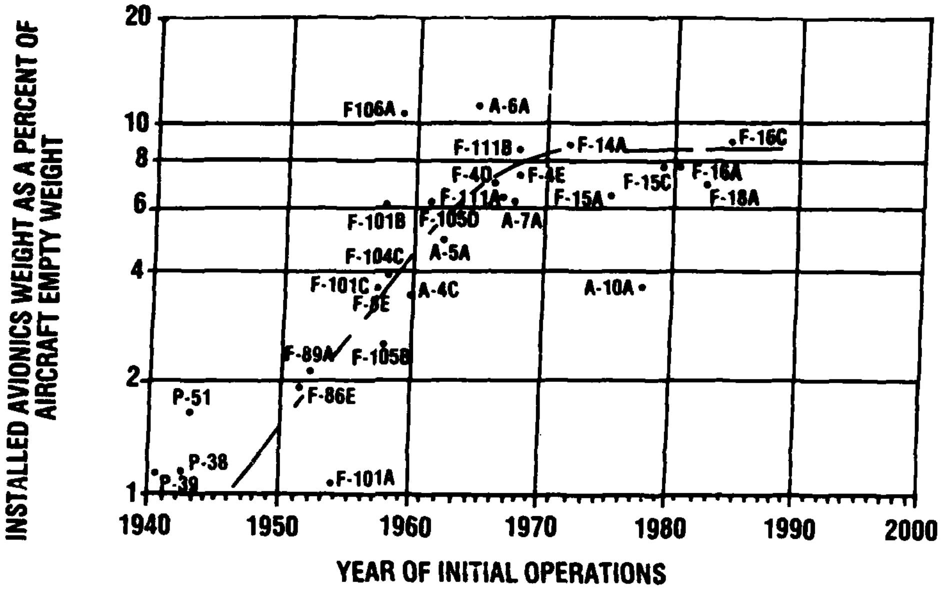


Figure 4

The technology advances in the last two decades in the area of analog and digital avionics have added tremendously to weapon system effectiveness. An example of these added capabilities and functions is in the area of the attack radar. Figure 5 shows the increase in radar modes and functions from the range-only-radar in the early 1950s to the F-15E multi-mode radar of the late 1980s. This same trend is evident in other avionics subsystems and equipments.

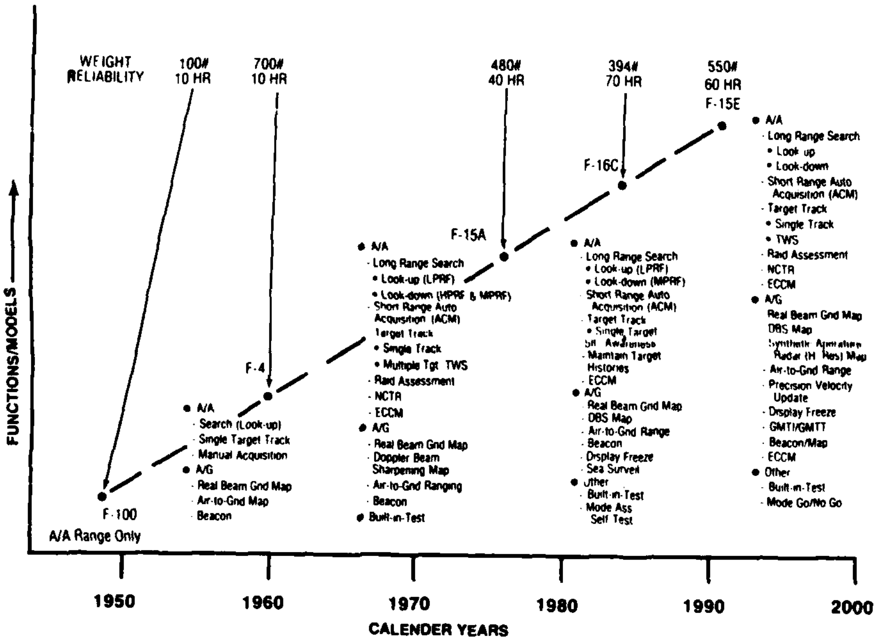


Figure 5

It should be kept in mind that these increases in avionics functions and capabilities have been provided while increasing the reliability of the avionics. Figure 6 shows the relationship between technology used in radars versus the number of parts in radar versus the reliability of the radars. This figure shows the reliability of existing radars; as well as, the expected reliability when Very High Speed Integrated Circuits (VHSIC) and Microwave Monolithic Integrated Circuits (MMIC) are used in future radar design. AS shown in Figure 6 a four fold increase in radar mean flight hours between failures is expected with the use of VHSIC and MMIC technology.

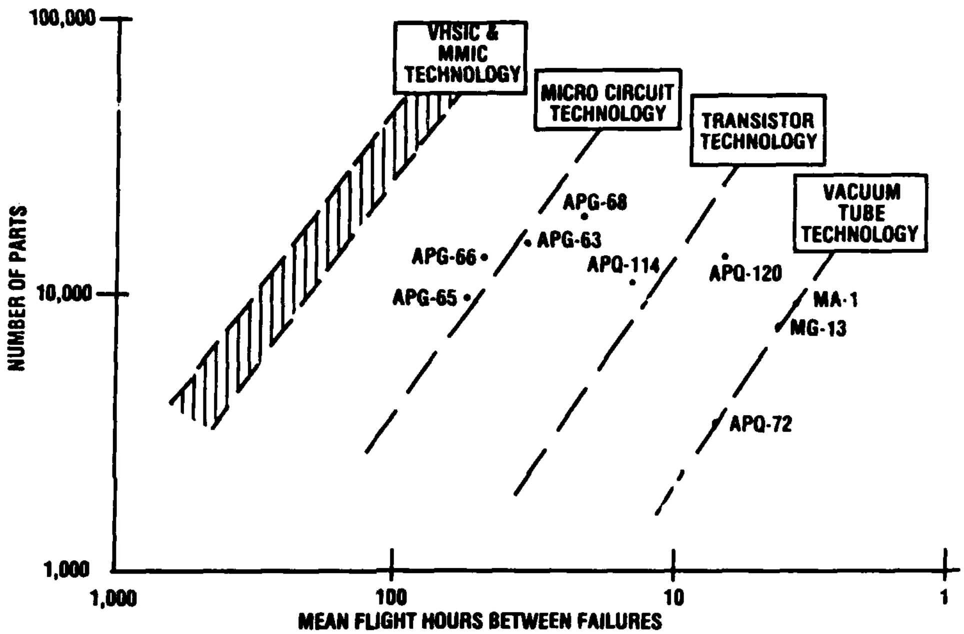


Figure 6

With the advent of the digital computer, an additional element is significantly impacting avionics development cost and schedules. This element is software. The magnitude of the software task has increased by a factor of at least five in the last ten years. The total on-board computer capability for fighter aircraft was adapted from data in Reference 1 and depicted in Figure 7. It is expected that this growth in computer capability shall continue. Available digital computer capacity has resulted in significant increases in software development efforts. Rapid software growth has resulted in a poor track record with software programs.

Poor estimates of the size and complexity of the software programs and tasks have caused schedule slips and budget overruns. It should be realized that the operational flight program (OFP) or on-board software is only the tip of the iceberg where software is concerned. Figure 8 depicts the software tasks associated with providing a proven software program. Past history indicates that development of operational flight software for fighter aircraft requires about seven (7) manhours per line of code. This manpower represents end-to-end productivity of software development from requirements analysis through flight test validation. The cost of the development of software has risen to the point that it is now approximately equal to the cost of hardware development. If productivity of software development is not improved, future software cost will exceed hardware cost. To achieve this improvement, more experience with the programming language is needed and better tools, improved programming practices, software reuse and better simulations must be implemented. To reduce cost of software, improvements in productivity must be accomplished.

An avionics area closely related to reliability and software capacity is the area of maintainability. The amount of built-in-test in avionics systems has increased; however, the adequacy of the built-in-test has been marginal, resulting in excessive maintenance costs. Recent advanced developments have been aimed at improvements in this area.

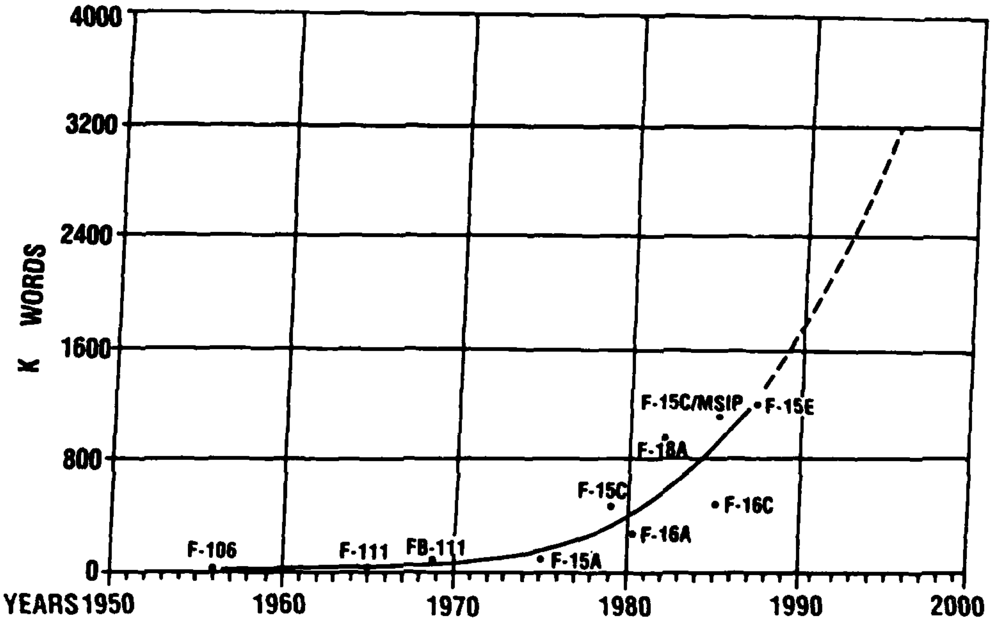


Figure 7 (Reference 1)

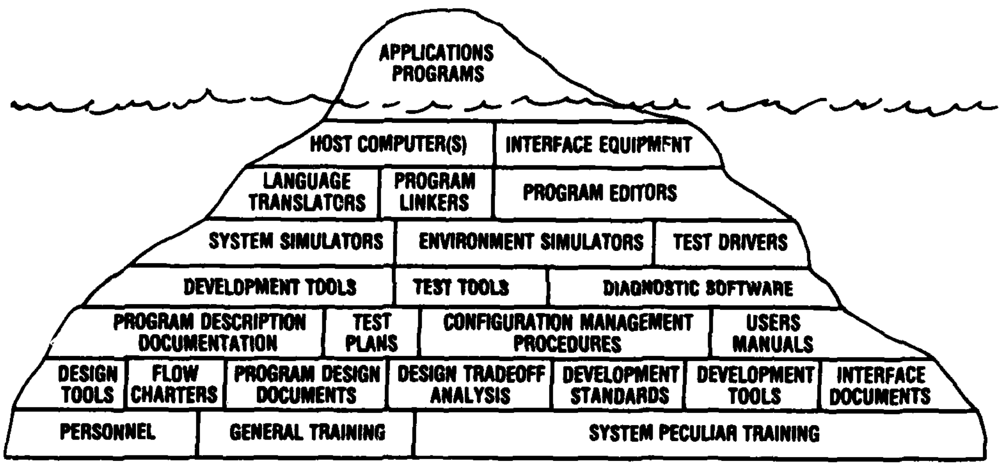


Figure 8 (Reference 5)

Avionics architecture evolutions, avionics weights, avionics capabilities and functions, avionics reliability and maintainability, and avionics software have been reviewed. The costs of avionics will now be examined. Three avionics cost perspectives were investigated. These are total avionics cost in fiscal 1986 dollars, cost per pound and percentage of aircraft fly away cost expended on avionics. Figure 9 shows the cost of some of the fighter avionics systems. The figure shows that a significant reduction in avionics cost was realized when the micro-circuit technology replaced vacuum tube and transistor technology used in the F-106 and F-111. It would be hoped that such a reduction would occur when VHSIC and MMIC technology is introduced; however, there is no evidence this will occur. The major reason seems to be the limited quantities of circuits used and non-optimum production rates.

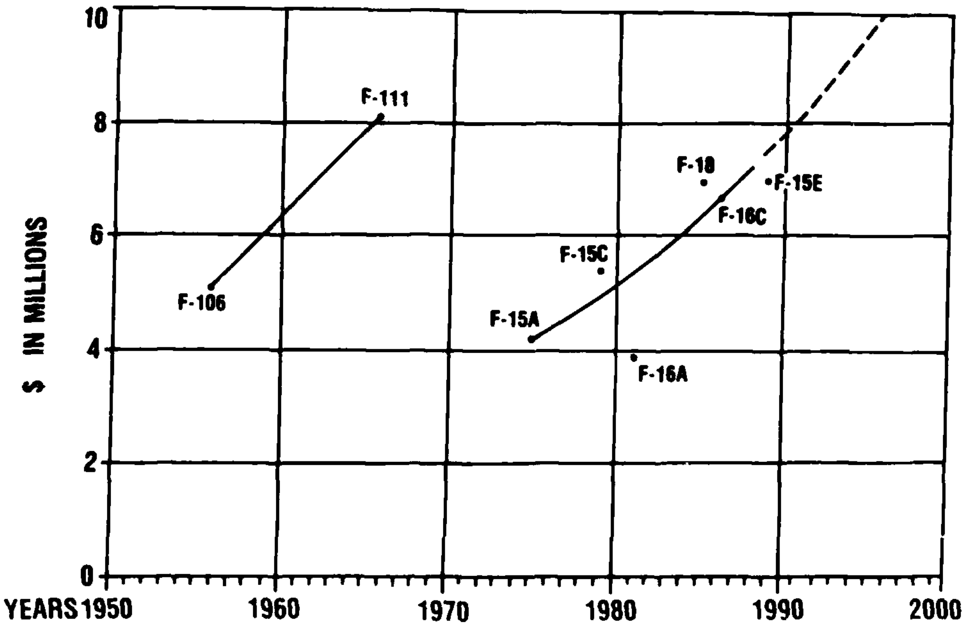


Figure 9

If costs are looked at with respect to the weight of the avionics systems one sees the cost per pound is increasing significantly. This trend is shown in Figure 10. While the weight of avionics in fighter aircraft is fairly constant, the cost of the components is increasing. Since many more functions and capabilities are being provided by the avionics today, the added capabilities are responsible for the additional costs.

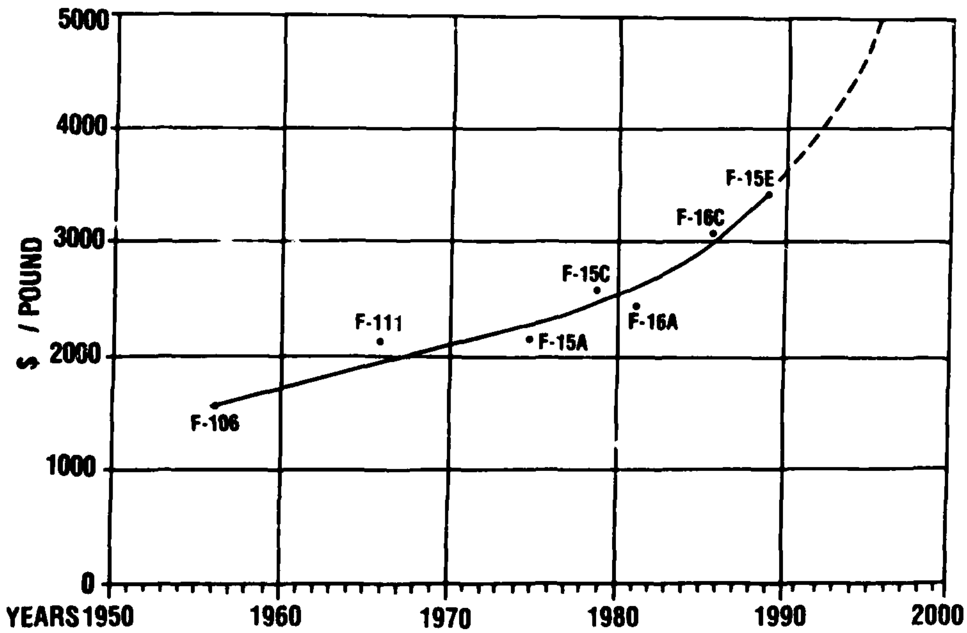


Figure 10

Figure 11 shows that the avionics in fighter aircraft are accounting for a higher and higher percentage of the aircraft fly away costs. If this trend continues, the acquisition cost of avionics will approach thirty-five percent of the aircraft fly away cost for the next generation fighter aircraft.

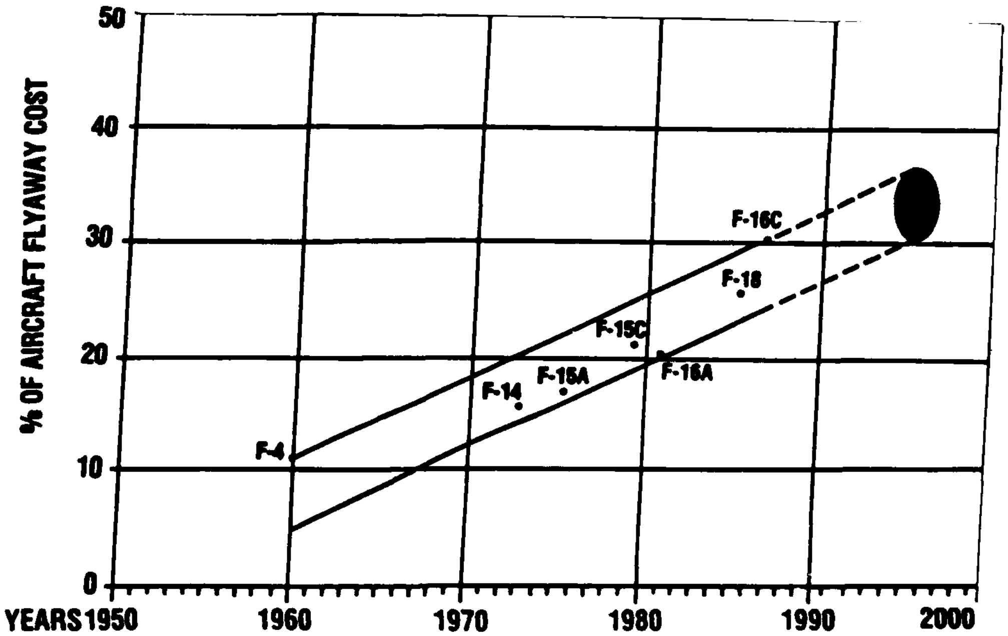


Figure 11

In summary, the avionics trends show that significant improvements in capabilities, performance and functions have provided a significant improvement in weapon system effectiveness and survivability. While these improvements have taken place, weights have reduced and reliability has increased. Software development has become a major avionics task. The cost of avionics in fighter aircraft has increased to the point that it now represents approximately thirty percent of the aircraft fly away costs. The increase in time from concept to initial operational capabilities is primarily due to increased concept definitions and demonstrations/validations phases.

FUTURE APPROACHES

To prepare for the next generation avionics suites which offer significant advances in capability and availability at an affordable cost, the U.S. Air Force has undertaken technology projects to move toward integrated avionics. Future avionics will include functional integration, information sharing, automatic fault tolerance and redundancy, common hardware, and standard software and processor instruction sets. Today's avionics use the traditional discrete "black box" (functionally independent) approach using medium and large scale integrated circuits, discrete radio frequency components such as; traveling wave tubes, mechanically scanned antennas, integration using digital processing, twisted pair wire multiplex buses, and JOVIAL higher order language software. Tomorrow's avionics will be an integrated suite using very large and very high speed integrated circuits, microwave monolithic integrated circuits for active element radio frequency systems, fiber optic multiplex buses, and Ada higher order language software. These avionics will share resources both hardware and software, between functional areas such as, radar and electronic warfare.

Very high speed integrated circuits (VHSIC) is a major element of the future avionics approaches. VHSIC offers the potential for significant performance improvements through increased computatioral speed. Increased computational speed is achieved partially through reducing inter-component distances. This means significantly reduced sizes of the circuits. This technology gives the potential of marked improvement in reliability if some of the reduced volume is reinvested to reduce the equipment operating stresses (cooling, vibration, etc).

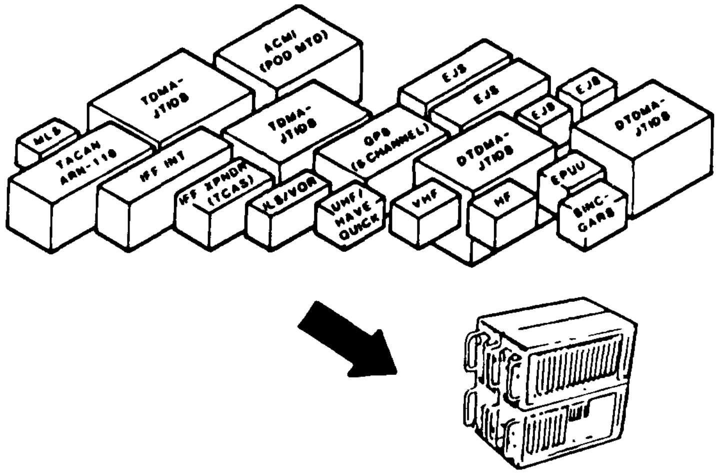
As VHSIC is essential in the area of digital avionics, microwave monolithic integrated circuits are critical for future radio frequency systems; such as, radar and electronic warfare. This technology can provide increased performance, improved fault tolerant design, and reduced life cycle cost. Presently the acquisition cost of active element modules is too high. These modules are of hybrid design and the use of monolithic technology is forecast to alleviate this problem. An example of the expected cost reduction using monolithic technology is shown in Table 1. The data was derived from the Air Force Solid State Phased Array Program and reported in Avionics Week and Space Technology (Reference 4).

	HYBRID MODULE	MONOLITHIC MODULE
TRANSISTORS	14	0
INTEGRATED CIRCUITS	5	2
DIODES	24	0
CAPACITORS	20	9
FILTERS	4	4
RESISTORS	4	0
MICROSTRIP SUBSTRATES	12	0
CARRIER PLATES	6	0
Total Parts	89	15
INTERCONNECTIONS	364	60
ASSEMBLY TIME	15 HR	1 HR
COST PROJECTION	$2000/ELEMENT	$500/ELEMENT

Table 1

As can be seen from the comparison, the cost of the hybrid module is primarily labor while the monolithic module is expected to be primarily material.

An example of the savings in size and weight due to VHSIC, hardware integration and resource sharing is the Integrated Communications, Navigation, Identification Avionics (ICNIA) development program. This effort is depicted in Figure 12.



DISCRETE SUBSYSTEMS		PRODUCTION ICNIA	
SIZE (CU FT)	WT (LBS)	SIZE (CU FT)	WT (LBS)
8.0	585	4.0	230.0

Figure 12

This approach is aimed at incorporating functional integration, functional redundancy, resource sharing, automatic reconfiguration, graceful degradation and extensive built-in-test. It is expected that this approach will reduce the logistics burden and increase operational readiness at a lower cost than the approach of using independent discrete systems.

Another area which needs to be developed to provide future target acquisition needs at an affordable cost, is sensor fusion. In the past target acquisition sensors have been independent and operated automously. For example, the passive receivers for radio frequency (RF) warning and identification were used for electronic warfare while the radar in the system was used for offensive attack. In the future, to keep performance requirements to a level which is affordable, sensor fusion (combining capabilities of multiple sensors to achieve a function); such as cueing of one sensor with information from another, will be required to simplify individual equipments. Sensor fusion will also improve the crews ability to manage the avionics system. It will be combined with the use of common modules or common hardware in each of the sensors to reduce overall acquisition cost. These modules are primarily in the digital processing area. Higher speed fiber optical multiplex buses will be required to implement this approach.

A critical area in future fighter aircraft avionics is the area of maintenance. In the past, the Air Force has had a three level maintenance concept. These levels are flight line, intermediate shop, and depot. The present avionic systems have built-in-test to isolate failures to the Line Replaceable Unit (LRU). The failed unit or units are removed from the aircraft and taken to the intermediate shop for fault isolation to a shop replaceable unit (module). The failed module or modules are shipped to a depot for repair. To examine the benefits of changing from a three-level to a two-level maintenance concept, an in-house USAF study was conducted. This study examined the relative life cycle costs of several combinations of maintenance concepts and technology integration. The study was based on the estimated costs of operation and support plus the avionics intermediate shop and spare parts to support 1000 aircraft for twenty years at a flying rate of 300 flight hours per aircraft per year. The results of this analysis are shown in Figure 13 as reported in the Defense Electronic Magazine (Reference 3).

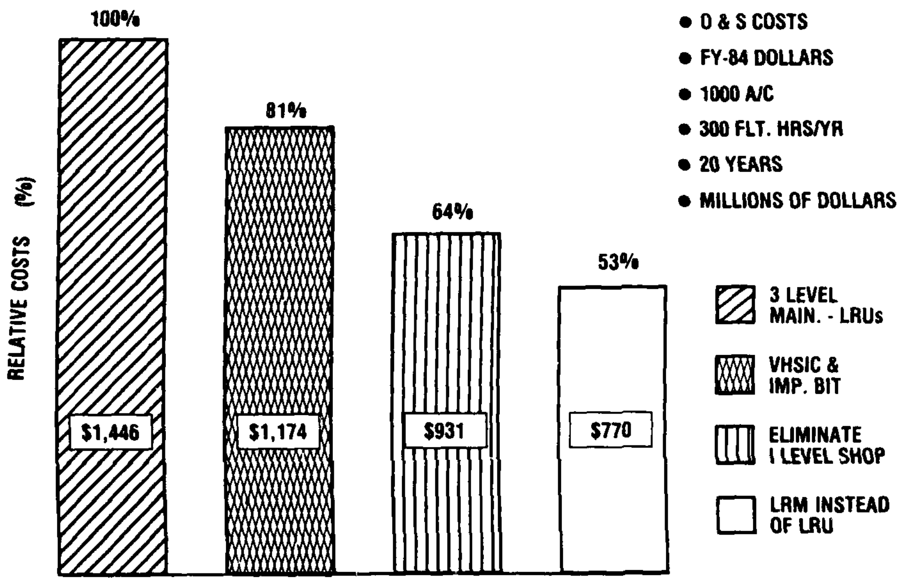


Figure 13

The various approaches were compared to todays technology and the three-level maintenance concept. The study showed that operating and support cost could be reduced to 81% of the present cost by introducing VHSIC and improved built-in-test. In the next scenario, the avionics intermediate shop was eliminated and the LRUs isolated by built-in-test were shipped directly to the depot for repair. This approach resulted in a 36% reduction. The final scenario consisted of modular design using VHSIC, with built-in-test capable of isolating failures to a line replaceable module. The savings approached 50%. While these numbers are not hard and fast they do provide an indication of sizeable cost gains which can be made in the maintenance area. The built-in-test in the avionics to isolate to a line replaceable module does increase the software program and acquisition cost. As can be seen the intermediate shop is a significant burden. It takes over four C-141B's to deploy a wing's worth of the F-16 intermediate shop. It is complex, expensive, manpower intensive and is vulnerable. Intermediate shop replacement dictates improved reliability and improved built-in-test. (Reference 2).

To help ensure that avionics continues to see improvement, USAFs Aeronautical System Division has restructured its avionics development and reliability approach. The new approach is called Avionics Integrity Program. It incorporates the technical and programmatic elements of the highly successful Air Force Structural and Engine Integrity Programs combined with traditional proven avionics approaches. The purpose of AVIP is to establish a technical and management process to improve avionics system availability at reduced life cycle cost. The approach is to organize a disciplined engineering and management process in stages to focus on total environment stress on avionics, the durability requirements, and quality assurance strategy based upon failure investigation and corrective action using analysis, measurements, tests and use of follow-up control through the deployed force maintenance and operation. The process is based upon definition of the operational usage and environment for the avionics, understanding the failure processes, analysis for design and early verification, early verification of the manufacturing processes, early testing to identify and verify correction of design deficiencies, positive control of problems, and verification in actual usage and environment. This process is depicted in Figure 14.

STAGE I (DESIGN INFORMATION)	STAGE II (PRELIMINARY PLANNING)	STAGE III (DESIGN)	STAGE IV (COMPLIANCE AND PRODUCTION)	STAGE V (FORCE MANAGEMENT)
DEFINE: • OPERATIONAL REQUIREMENTS - HOST VEHICLE - FLIGHT ENVELOPES - MISSION PROFILES - MISSION MIXES • MAINTENANCE CONCEPT - PREVENTATIVE - CORRECTIVE - ON/OFF EQUIPMENT • ENVIRONMENTAL CONDITIONS - OPERATING - LOGISTICS • INTERFACE - COOLING - POWER	DEVELOP: • OVERALL PLANNING - AVIONIC INTEGRITY MASTER PLAN - PROCESS DESCRIPTION • REQUIREMENTS INTERPRETATION • DESIGN CRITERIA • TRADE STUDIES • PRELIMINARY PREDICTIONS	ESTABLISH: • MANAGEMENT AND ENGINEERING ORGANIZATION TO ASSURE INTEGRITY • ENVIRONMENTAL TEST SPECTRA ACCOMPLISH: • ENGINEERING DESIGN TO SATISFY INTEGRITY REQUIREMENTS • MANUFACTURING PROCESSES TO YIELD AVIONICS TO SATISFY REQUIREMENTS	DEMONSTRATE/VALIDATE: • DESIGN AND MANUFACTURING PROCESSES MEET INTEGRITY REQUIREMENTS • PRODUCTION QUALIFICATION • VALIDATION OF ENVIRONMENTAL DATA WITH GROUND AND FLIGHT TEST • QUALITY CONTROL	ACCOMPLISH: • DATA GATHERING ON DEPLOYED SYSTEMS • ESTABLISHMENT OF CORRECTIVE ACTIONS

Figure 14

To summarize, next generation avionics will utilize VHSIC, microwave monolithic integrated circuits, fiber optic high speed data buses, increased integration with advanced architecture, sensor fusion, shared hardware, software standards with reusable software, information processing, improved maintenance with integrated diagnostics, improved built-in-test with two-level maintenance, improved avionics environment and integrated functional and performance requirements.

CONCLUSIONS

Avionics technology advances in the past have added tremendously to the effectiveness of Air Force weapon systems. Avionics provide continually increasing functions, performance and reliability while not increasing the weight installed in the aircraft. The reliability of the avionics has increased. To prepare for the next generation avionics which will provide additional advances in capability, new approaches using VHSIC and microwave monolithic integrated circuits will be required to allow acquisition of these systems in a budget constrained environment. To control cost, the avionics requirements and performance must be controlled to provide "sufficient" performance not "best" performance. In addition, coordination and cooperation between equipments and subsystems within the avionics system must be provided rather than, each trying to solve all problems. To improve operating and maintenance costs, new technology must be used along with providing improved environment for the avionics in the aircraft. To reduce initial acquisition costs, hardware must be shared between equipments and subsystems and software productivity must be improved using modular reusable standard software and improved simulations. The maintenance of new avionics systems must be improved to reduce dependence on intermediate shop support by improved built-in-test, fault tolerant design, reconfigurability and improved avionic circuitry. To improve the length of time required to acquire new avionics, reduced decision times and an approach which initially takes lower risk alternatives with an architecture that allows preplanned product improvement when the technology is available. The use of standards and common hardware can also reduce schedules but at the expense of incorporation of new technologies. The challenge is to use these new technologies and avionics approaches to provide sufficient capability within budget and schedule constraints. Because of the need to counter the future threats and avionics being the single largest factor in combat effectiveness and system availability, avionics costs will continue to rise but the judicious use of the approaches, techniques and the structured design process described, control of the cost increases can be accomplished.

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REDUCING TIME REQUIRED FOR THE DEVELOPMENT OF AVIONIC SYSTEMS

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SUMMARY

The current rapid increase in avionic system complexity causes difficulties in both defining and implementing the system requirement. Errors in the requirement and in the implementation of the requirement lead inevitably to an extension in the time necessary for system development and consequently to an increase in the cost of the developed system. This paper describes the avionic system onboard the Experimental Aircraft Programme (EAP) and the design process used on that system. In particular the effectiveness of:

a) rapid prototyping as a means to arrive at a sensible requirement;

and

b) implementation, via Semi Automated Functional Requirement Analysis (SAFRA), is outlined.

A resume of the results from the EAP is used to show that this structured approach to design using both rapid prototyping and SAFRA does reduce the time required for avionic system development.

1 INTRODUCTION

The term avionics is seemingly elastic, we no sooner put together a definition of 'avionics' than the definition needs to be extended to incorporate developments to existing subsystems or wholly new subsystems. Most people would accept that radar is part of the definition, but current radars have typically 10 times as many modes as their 1950's predecessors. New devices such as laser and low light television have spawned new subsystems. Aerodynamicists now require fly by wire systems as a means to realise the full potential of the airframe. Structural engineers require load alleviation systems to minimise structure weight.

All of these innovations and developments provide undoubted improvements in the operational effectiveness of individual aircraft. Group operational effectiveness has been enhanced by the use of communications, command, control and information (C^3I) systems and thus a further demand has been placed on the avionics systems.

Procurement executives have eagerly adopted these technical advances, rightly seeing them as a means to retain military superiority over our adversaries. They have also recognised that this technology costs money and have therefore tried to trim costs in other areas, notably airframe and aircrew training, by reducing the number of operators on each platform. So at the same time as the system complexity is increasing rapidly the number of operators available to control the system is decreasing: more automation is necessary; more attention needs to be paid to the man machine interface; more emphasis is placed on the avionic system.

It is all too easy, in the face of these rapid changes and under the constraints of a tight timescale, to rush through a defective system requirement and then to compound the felony by implementing this requirement incorrectly. The resulting remedial programme extends the development phase and is very costly.

This paper describes how, on the recent Experimental Aircraft Programme (EAP), we set out to produce a sensible system requirement and implementation, and outlines the effectiveness of the approach adopted.

2 EAP OVERVIEW

The EAP started in December 1983 involved British Aerospace, Aeritalia and numerous other industrial partners throughout Europe. The objective of the programme, which was funded jointly by Government and Industry, was to demonstrate technology appropriate to the next generation of fighter aircraft. It was intended to show not only the operational benefits of this technology but also the means to introduce it cost effectively. The programme culminated in a single seat demonstrator aircraft. The technology included covered the fields of aerodynamics structures/materials and systems. The aerodynamic and structural/materials innovations on EAP provide sufficient subject matter for papers in their own right (for general background see reference 1); the remainder of this paper will concentrate on the avionic systems innovations and the design processes used to introduce these innovations.

The avionics suite for EAP is shown in simplified block diagram form in fig 1 and included the 'glass' cockpit shown in fig 2. The architecture can be subdivided into 3 main areas(local area networks): flight control system; avionics; utility service management system (USMS).

2.1 Flight Control System

The quadruplex digital flight control system on EAP is a derivative of that used on the Jaguar Active control technology (ACT) aircraft, no mechanical backup is provided. The four identical flight control computers allow the system to sustain two major failures without endangering the aircraft. In addition to hosting flying surface gain scheduling software these processors house software for failure management, reversion logic and built in test. The FCS also includes four aircraft motion sensor units (AMSUs), two air data computers (ADCs) and four actuator drive units (ADUs). Whilst the foreplane, intake varicowl and wing leading edge devices are driven directly from the FCS computers, the wing trailing edge devices and rudder are driven from the aft mounted ADU's which are connected to the computers by serial digital links. A digital data bus is also used to connect the air data computers and motion sensors to the Flight Control Computers.

The FCS computers pass on air data to the avionics and USMS via the two main MIL STD 1553B data buses. In addition they process motion sensor information to provide data for the standby attitude and heading reversionary instruments.

2.2 Avionics System

The avionics system comprises three integrated subsystems: navigation; communications; displays and controls. Communication between these subsystems is achieved via a dual redundant Mil Std 1553B data bus. Discrete links were avoided except where cost and integrity reasons dictated otherwise.

The navigation subsystem comprises an inertial navigation processor, Tacan and radar altimeter. Data provided by the subsystem includes attitude, heading, velocity, track, altitude, present position and time.

The communication subsystem is controlled by an integrated communication and audio management unit (CAMU).

Displays and controls is by far the largest avionic bus subsystem. The two identical waveform generators are each capable of driving three multi function colour displays and a wide angle head up display HUD. Raw control data from the switches mounted on the stick, throttle lips, side consoles glareshields and multi function displays is processed by two identical cockpit interface units (CIFUs) prior to distribution on the Avionics data bus.

2.3 USMS

The utility service management system provides for:

- engine control and indication;
- fuel management and gauging;
- hydraulics system control including undercarriage, wheel brakes and anti-skid devices;
- environmental control;
- secondary power system;
- miscellaneous systems including liquid oxygen control, electrical generation, pitot head heating, emergency power unit.

Many advantages accrue from utilising a USMS, not least being the ease with which it can be integrated with the avionics system and hence the cockpit displays and controls.

In summary the overall system comprised: 3 local area networks; 14 processors, 300K of software which was produced by 7 companies in 3 countries. Having described the system we will now go on the describe the design process used to define the system.

3 DESIGN PROCESS

In discussing the design process we will restrict ourselves to software design. The justification for this limitation is twofold. Firstly British Aerospace does not produce avionic hardware, this responsibility is ceded to a wide range of avionic companies. Secondly, as can be deduced from the foregoing description of EAP, the functionality and control of avionic systems is increasingly expressed via the use of software in general purpose digital processors see fig 3.

As noted earlier if the system designer gets it wrong at either the requirement stage or the implementation stage the development programme will lengthen and the cost of ownership of the fully developed system will increase. In advance of writing the requirement, the design process must be sufficiently flexible and responsive as to allow the designer, operator and customer to inject their ideas; after the requirement is written, the process must be rigorous enough to minimise implementation errors.

3.1 The Requirement

There is no problem in defining the requirement if the system being designed is similar to a system designed previously. In this situation very few errors are introduced at the requirement stage (see for instance reference 2). Unfortunately, given the gestation period of fighter aircraft and the rapid developments in the field of avionics, the systems carried on succeeding generations of aircraft bear little resemblance to their predecessors. The problem for the designer is to identify a sensible requirement for the system, at a time when none of the real aircraft software and little of the hardware exists. The only means of providing an understanding of what the system will look like is via simulation. At this stage in the programme, the approach has to be evolutionary. The designer's preliminary ideas are simulated and the simulation is demonstrated to the customer or his representative, the service operator. This demonstration will in general provoke suggestions for modifications which may be incorporated into the simulation. Hence via succeeding iterations.

a) the simulation becomes more representative;

b) the designer, operator and customer become more aware of the potential of the system being simulated.

Eventually the designer is sufficiently confident, based on his experience with this simulated system, to write the requirement for the real system. This process of successive iterations of simulation software is called rapid prototyping (see reference 3).

3.1.1 Rapid Prototyping

Over the years since the second world war the man machine interface has become increasingly fraught due to the increase in system complexity and the reduction in the number of aircrew; figure 4 shows the increase in the number of displays and controls per operator. Because of this deteriorating situation it was decided on EAP to use a 'glass' cockpit which would go some way towards alleviating operator workload. Since this concept of a 'glass' cockpit was new to BAe it was decided that we should produce a rapid prototype of the cockpit. It should be noted that in order to effectively prototype the cockpit it was necessary to prototype the operation of the subsystems. In the five year period preceding EAP go ahead, BAe had been building up generalised facilities which would allow prototyping of the man machine interface (MMI). These facilities, which were based entirely on commercial equipment, enabled prototyping of the MMI on EAP to be carried out in 3 phases as follows.

Phase 1 covered the development of display formats for use on the head down multi function displays. At this stage the format generator and architecture used were very rudimentary (fig 5) allowing only static formats to be represented, but format layout, symbology and colour usage could be investigated. The interface for this format generator is very user friendly, allowing tablet and mouse inputs. Typically it takes 1 hour to generate a reasonably representative display format; modifying the format thereafter can be done in a matter of minutes.

Phase 2 used a slightly more sophisticated rig and architecture (fig 6). The formats were still static but the rig allowed rationalisation of the formats appearing of the 3 multi function displays and in addition display switch moding could be investigated. Rationalization of the formats required regression to phase 1 noted above. Variations in display switch moding could be introduced by setting flags within generalized moding tree software housed within the host computer.

Phase 3 used a full dynamic simulation of the operation of the cockpit (fig 7) and was dependent upon prototyping simulations of all of the major subsystems. The rig operated in real time, and used seven processing areas federated on a Mil Std 1553B data bus. The pilots could 'fly' this simulation and hence define workload problem areas. The resulting change requests could be evaluated on both the format generator and the moding rig prior to incorporation into the full dynamic simulation. Hence the operation of the man machine interface and of the subsystems was modified and assessed until such time as the pilots were confident that the workload was operable through all phases of flight - the requirement could then be written.

The beauty of prototyping is that it is carried out whilst the design is still fluid. Modifications can be introduced on an informal pilot to engineer basis and paperwork is kept to a minimum. Contrast this with trying to introduce a modification to a service aircraft. Firstly the applicant has to confront a bureaucracy whose effect, if not their objective, is to block modifications. Even if the modification is approved, integrating it into a frozen architecture and then retrofitting to a fleet of aircraft is an arduous and extremely expensive task.

Prototyping does require front end investment in facilities and manpower but this is more than recouped by the reduction in the number of in service modifications, or put another way, by the reduction in the time required to develop the system. Having achieved a sensible requirement via the use of prototyping the next task is to implement that requirement.

3.2 IMPLEMENTATION

BAe Warton was responsible for the production of the avionics and USMS software; we had no previous experience of producing airborne software. Most of the engineers involved had not worked with real time software and none of them had produced airborne software. This shortfall in experience forced us to study the attributes which were required for the process to be used during the design and production of the airborne software. General engineering experience indicated that in order to facilitate:

a) management - the process should be reduced to a series of steps;

b) quality control - the output from each step should be auditable

c) productivity - each step should be computer aided.

The process eventually adopted was designated Semi Automated Functional Requirement Analysis (SAFRA) and is shown schematically in figure 8. After freezing the requirement, using prototyping, the implementation is achieved by a series of steps which progressively decompose that requirement into greater and greater detail. Eventually the requirement has been analysed to such an extent that transcription into a high level language (i.e. the coding step) is relatively simple. Subsequently the code is tested on commercial host processors and then the real aircraft target processors. This target testing is carried out initially on the avionic ground test rig and finally in flight. The productivity levels achieved on EAP using SAFRA are shown in figure 9, as can be seen the productivity is well up to expectations.

The quality of the software produced has been measured in terms of error densities (errors per thousand lines of code (KLOC)) and compared with those achieved on previous aircraft see fig 10. The upper line on this figure shows the number of errors which have managed to get through the host testing stage and have been picked up either on the avionics ground test rig or flight test.

The efficacy of the avionics ground test rigs has significantly improved within the past 10 years. This has been due to a change over from discrete point testing to dynamic testing in which the rig runs continuously in real time as per the aircraft. The impact of this change over was assessed on one of our previous aircraft over a 4 year period. During the two years prior to dynamic testing only 30% of the software errors arriving at the rig were detected during rig testing the remaining 70% were detected during flight. In the 2 years after the introduction of dynamic testing 80% of the errors were detected at the rig testing stage. If we compound the effect of this improvement in the effectiveness of rig testing with the reduction in the error density of the software delivered to the rig then we can infer the second line on figure 10, i.e. on EAP we would expect error densities of approximately 0.3/KLOC to be detected during the flight trial.

The foregoing analysis would lead us to expect a relatively short lead time to first flight and relatively few faults in the operation of the avionic systems in flight. Now let us consider the actual statistics of the programme.

4 EAP RESULTS

The whole EAP programme from the outset of the requirements definition phase to full software release from the avionic ground test rig took only 2½ years.

During the first 16 days of the flight trials programme the aircraft flew 19 times, with 3 different pilots - a measure of the confidence in the overall system.

There were no surprises i.e. the aircraft behaved much as the rapid prototype had done during the requirements definition phase.

As yet the flight trials programme has failed to detect any error in the implementation of the software requirement.

5 CONCLUSIONS

Rapid prototyping provides an effective means of evolving a sensible design requirement for avionic system software.

Rigorous decomposition of this requirement using SAFRA produces a marked reduction in the errors introduced during the implementation phase whilst maintaining high levels of productivity.

Both rapid prototyping and SAFRA require front end investment in both facilities and manpower: this investment is more than repaid by the resulting reduction in development time and consequent decrease in system cost.

Furthermore these same facilities are available to enable the smooth introduction of in service modifications such as are required by mid life update programmes.

6 REFERENCES

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ACKNOWLEDGEMENT

I would like to thank my colleagues at BAe Warton for their help in preparing this paper.

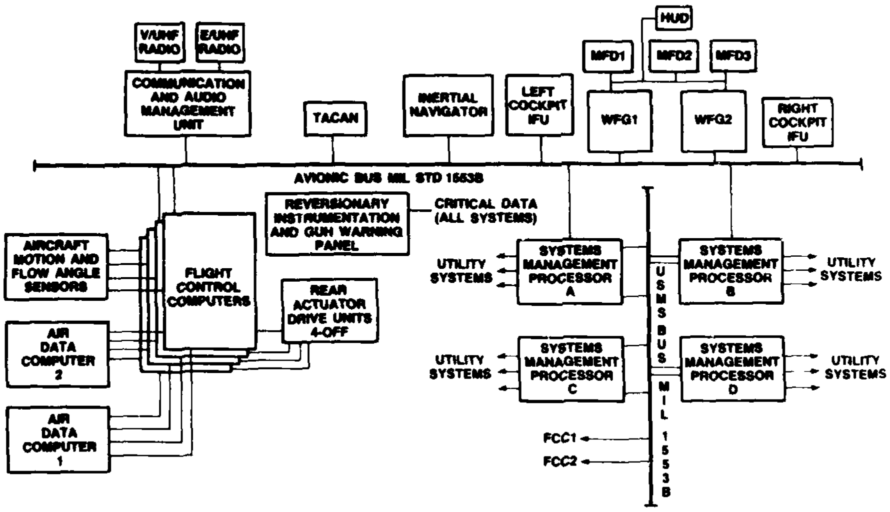

FIGURE 1 EAP OVERALL SYSTEMS SIMPLIFIED ARCHITECTURE

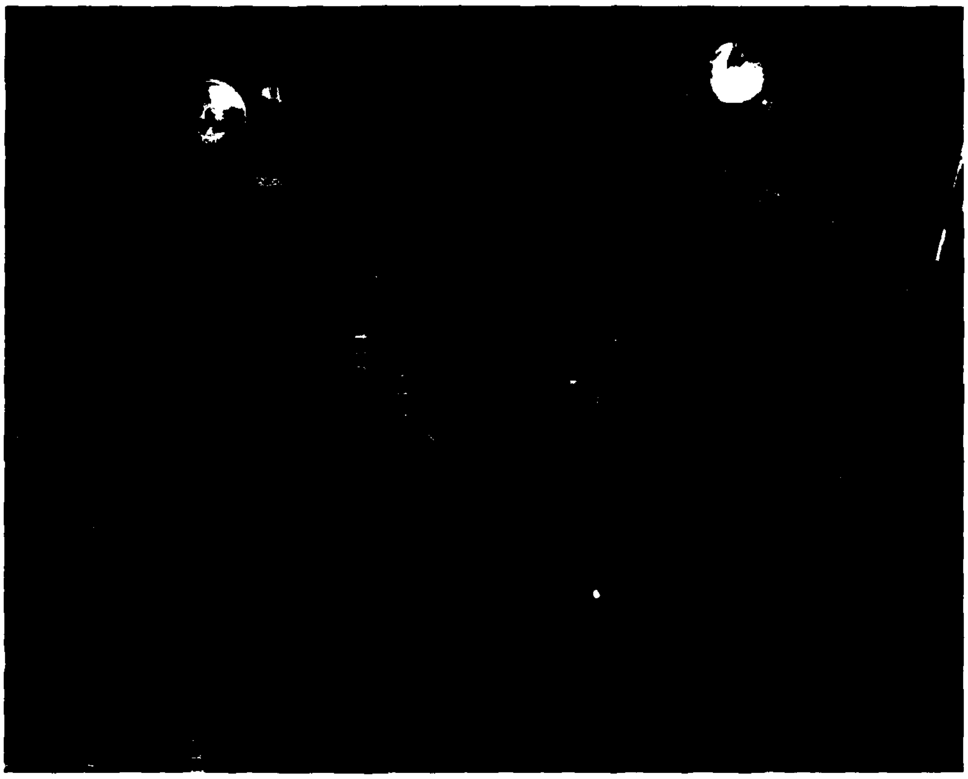

FIGURE 2 EAP COCKPIT

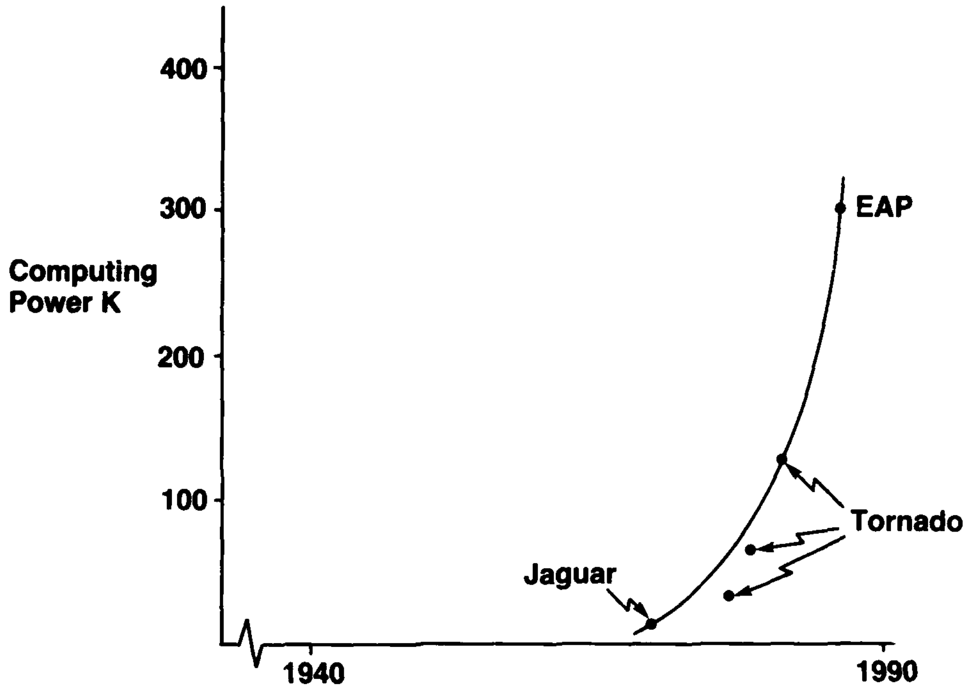

FIGURE 3 OPERATIONAL SOFTWARE GROWTH – MILITARY AIRCRAFT

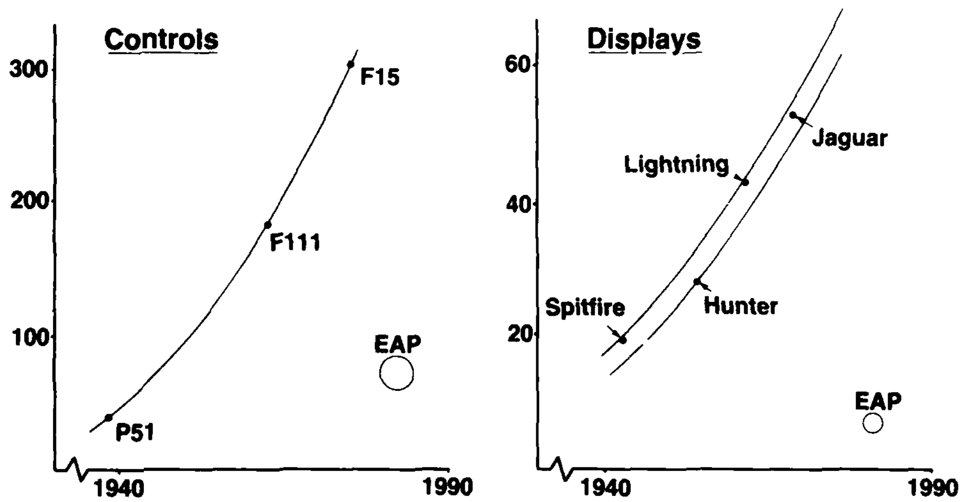

FIGURE 4 OPERATOR WORKLOAD

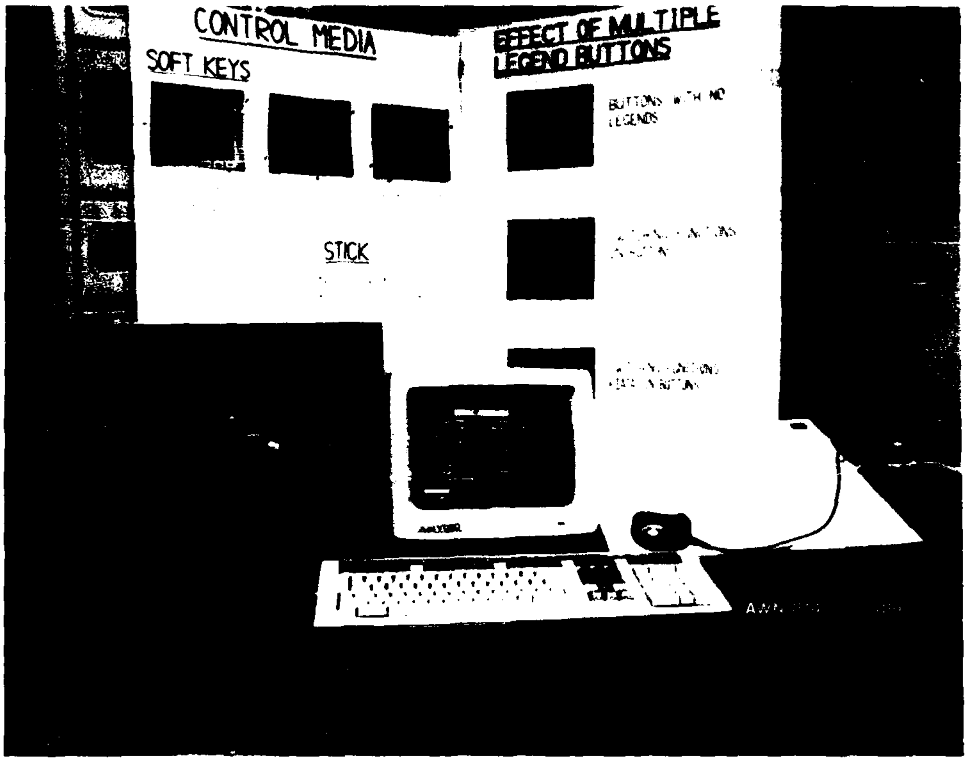

FIGURE 5a FORMAT GENERATOR

FIGURE 5b FORMAT GENERATOR ARCHITECTURE

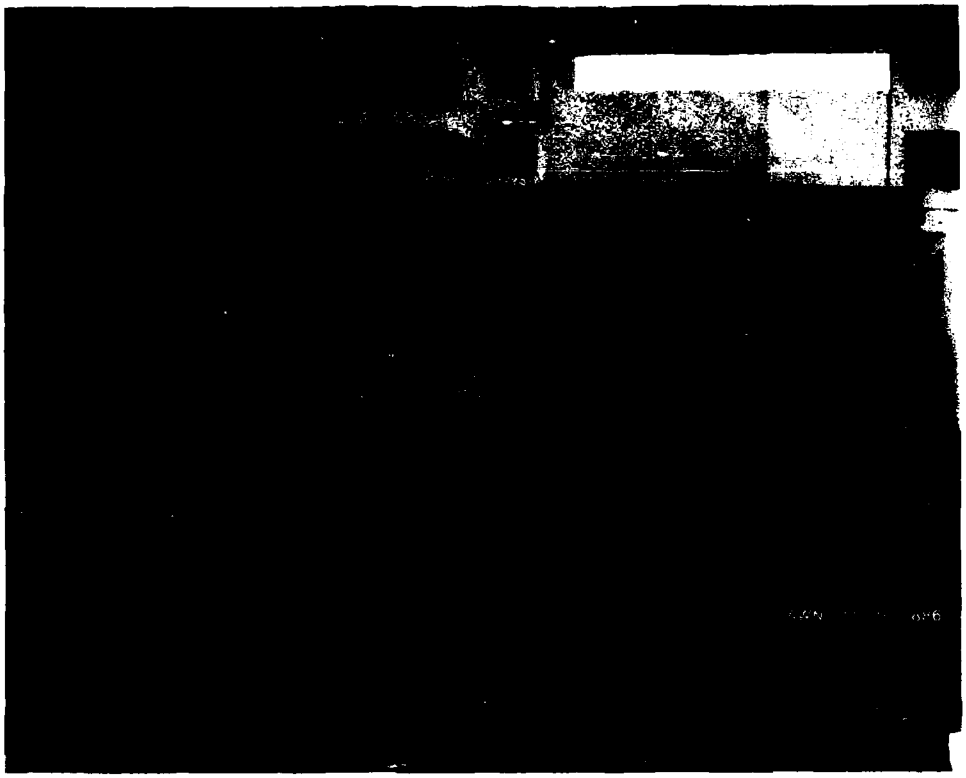

FIGURE 6a MODING RIG

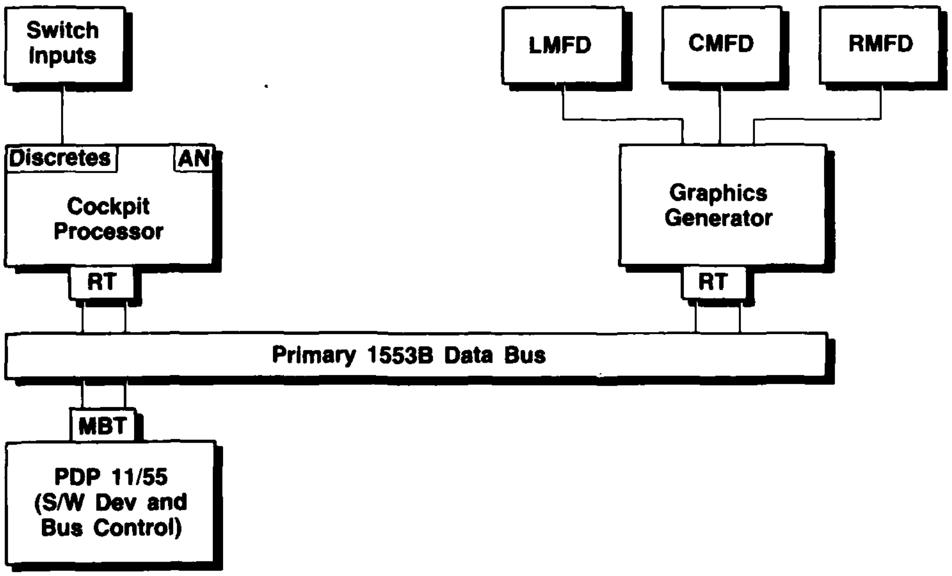

FIGURE 6b MODING RIG ARCHITECTURE

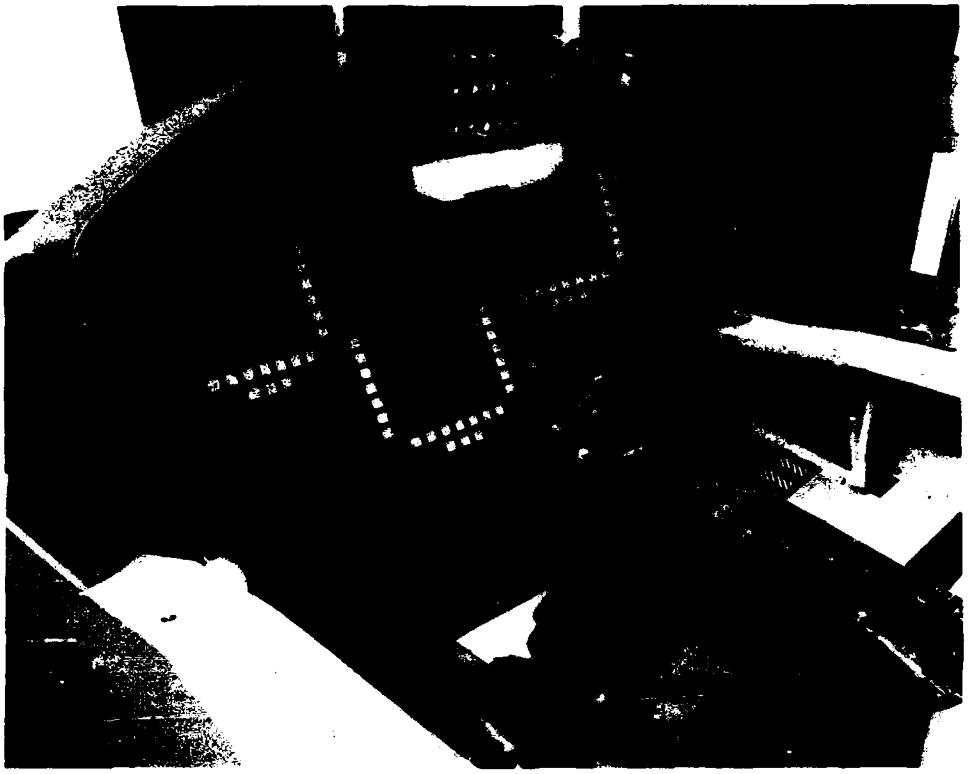

FIGURE 7a DYNAMIC SIMULATION

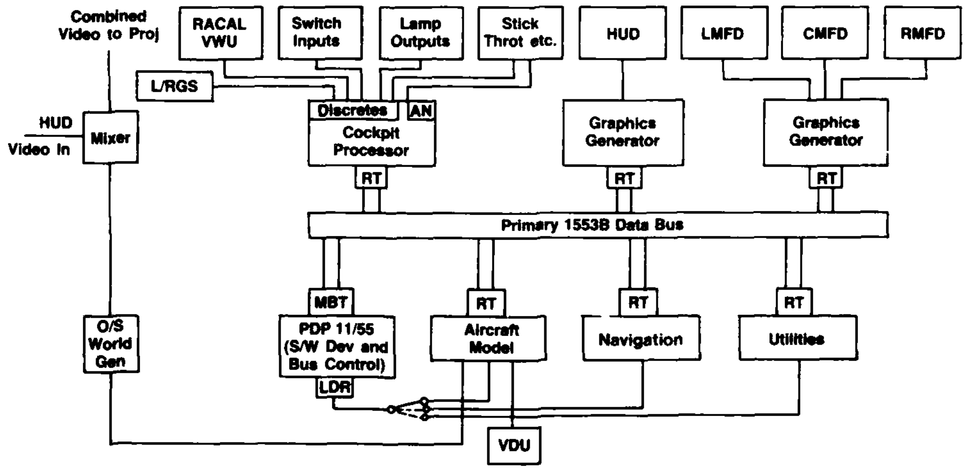

FIGURE 7b DYNAMIC SIMULATION ARCHITECTURE

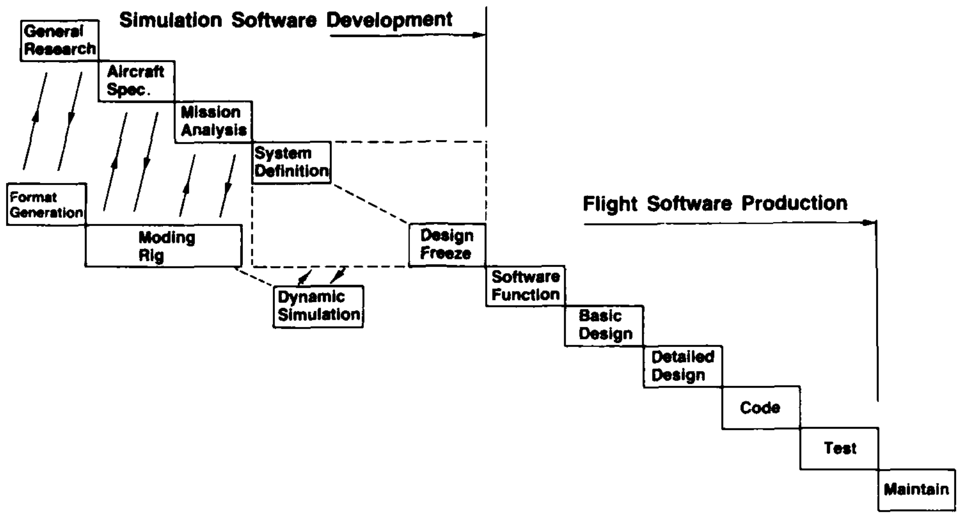

FIGURE 8 AIRBORNE SOFTWARE LIFE CYCLE

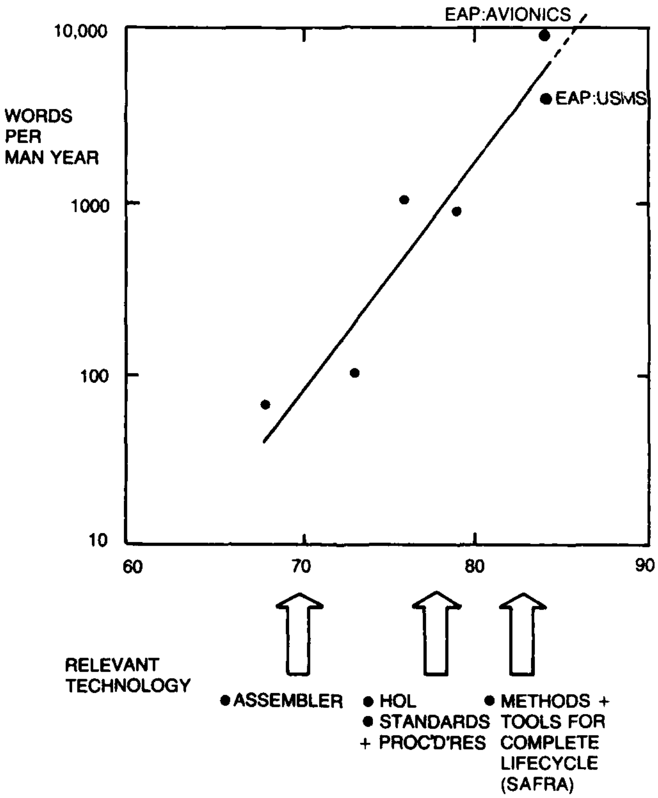

FIGURE 9 AIRBORNE SOFTWARE PRODUCTIVITY

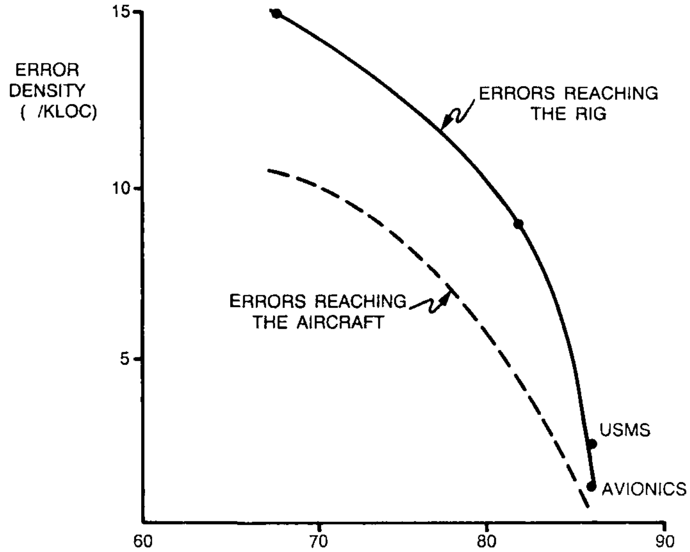

FIGURE 10 AIRBORNE SOFTWARE QUALITY

FIGURE 11 EAP IN FLIGHT

REDUCING ROTARY WING AIRCRAFT DEVELOPMENT TIME/COST THROUGH THE USE OF SIMULATION

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SUMMARY

Advances in simulation technology have made man-in-the-loop simulation highly capable, desirable and affordable for rotorcraft design and development. Since the use of simulation as a design tool is relatively new to the helicopter industry, the U.S. Army/McDonnell Douglas Helicopter Company AH-64A (Apache) is used as an example to evaluate the potential cost and time savings realizable through the use of simulation. It is shown that a modern full mission engineering simulator when used effectively co ld provide cost savings of several millions of dollars, and could duce helicopter development and flight test by at least a year or two. The means to exploit the full potential of simulation during rotorcraft design, development and test are also discussed.

INTRODUCTION

The use of man-in-the-loop simulation in designing fixed wing aircraft and their associated training systems is not new. However, until recently, the design and development of rotary wing aircraft via the use of simulation has been very limited. This was due to several factors. One significant limiting factor was the lack of fidelity available in low altitude flight simulation. This was particularly evident in the visual and sensor areas of simulation. It was also more computationally intensive to simulate the aeromechanical models and control laws of rotorcraft in real time as compared to the fixed wing counterpart. Simulation technology has made significant advances over the past 5 years in the area of computer image generated visual scenes, and simultaneously, computer hardware costs have been reduced because of the advances in microelectronics and chip technologies. The U.S. helicopter industry was motivated to adopt high fidelity man-in-the-loop simulation for helicopter design primarily because of the Army's LHX program. The LHX program mandated that design concepts be evaluated early in the development phase. Prior to the LHX Advanced Rotorcraft Technology Integration (ARTI) program, the major helicopter companies in the U.S. did not possess any significant high fidelity simulation capability with which to design their aircraft. Over the past three years, the U.S. helicopter industry including McDonnell Douglas Helicopter Company (MDHC) has made significant capital investments to acquire the capability to use simulation as a design tool (Reference 1). Furthermore, the Army has properly emphasized the involvement of the operator early in the conceptual design phases. This increases the importance of man-in-the-loop simulation in the early phases of the design and development of any new aircraft.

Therefore, in one design generation, the U.S. helicopter industry has gone from a minimal simulation capability to a requirement for real-time man-in-the-loop simulation as a primary design tool for both the aircraft development and its associated training devices. This paper will address the use of high fidelity man-in-the-loop engineering simulation to reduce schedule and cost during the design and development cycles. Since the use of simulation as a design tool is relatively new to the helicopter industry, an attempt is made here to evaluate the time and cost savings that might have been realized if the U.S. Army/McDonnell Douglas AH-64A (Apache) program would have had the benefit of a full mission simulator.

The paper is organized as follows. First, the Apache development is reviewed. This is followed by a discussion of some specific technical problems that were encountered and it is then shown how simulation could have aided design, development and test, had it been available. Examples of potential cost and time savings are given. Simulation requirements for effective support of future programs are also discussed.

AH-64A DEVELOPMENT

The AH-64A (Figure 1) was developed primarily for the anti-armor mission. It is the first helicopter designed to fight in day, night and adverse weather conditions. It also satisfies a very exacting set of requirements. These include the ability to perform attack missions at night, fly to the battlefield on instruments and attack targets with 1/2 mile visibility and 200 feet ceiling conditions. The Apache performance requirements include a vertical rate of climb of 450 feet/minute and a cruise speed of 145 knots, both at 4000 feet and 95°F temperature while carrying a mission payload of eight Hellfire missiles and 320 rounds of 30 mm ammunition. The Apache maneuver requirements include a 3.5 g pullup and -0.5 g pushover. The mission endurance required is 1 hour and 50 minutes. Vulnerability considerations required that no single 12.7 mm round or 23 mm round could cause mission abort. Crew survivability in a 42 feet/second vertical impact is also required. Actual performance of the Apache significantly exceeds these requirements in several areas.

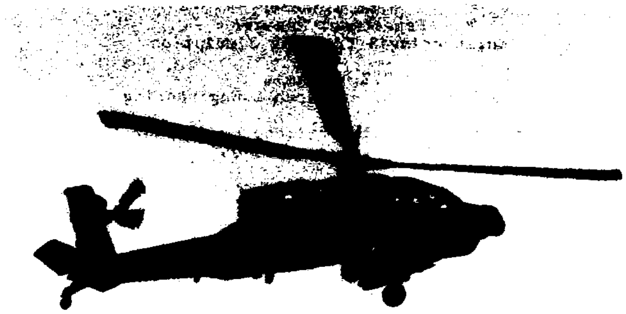

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Figure 1. The AH-64A (Apache)

The successful design of the Apache was the result of several technological advances in the areas of rotor systems, airframe, engine, drive system, control system, avionics and weaponization (Reference 2). The Apache was also the first helicopter program where several new systems were developed and integrated. These included the McDonnell Douglas Helicopter Company M230E1 Chain Gun, Rockwell AGM-114A Hellfire and the Martin Marietta target acquisition and designation sight/pilot night vision sensor (TADS/PNVS).

Development of the Apache helicopter was typical of the design process in the seventies. The design team did not have the benefit of an engineering simulator to use a design tool. The helicopter development involved extensive testing in areas such as structures, performance, controls as well as weapons and systems integration. Five flying prototype aircraft were built and design problems were analyzed and corrected on the aircraft as they were discovered. One of the constraints faced by the Apache team, like most other aircraft programs, was the lack of adequate time on the test range. A number of tests had to be conducted on the range and many of the problems, including software problems, were first identified only during flight test and integration. Despite the extensive and effective use of a hot bench facility, the test aircraft itself served as a software development medium, reducing its availability for other tests. Many of the issues pertained to resolving man-machine interfaces. These included display pages, symbologies, refresh rates, sequence of operations, switchology, etc. Resolution of these not only further restricted aircraft availability but also were labor intensive.

An engineering simulator would have made it possible to identify critical problem areas in the early stages of design and development rather than during the test and evaluation phase as it happened on the Apache. The availability of the simulator would have permitted solving these in the simulator and made the test vehicles available for other tests. For example, a software solution could have been developed, debugged and tested on the simulator, then verified for man-machine interface optimization on the simulator itself. It could have been then run on a hot bench interfaced to the simulator for system validation as well as mission validation. When all bugs had been fixed and a satisfactory solution had been obtained, it could have been implemented on the aircraft for operational validation. Considering the nature of the technical issues (Table I and References 3-5), a full mission simulator could have saved considerable money and time.

In the following section, a few of the technical problems are first discussed in general terms to provide an appreciation for the helicopter design process and the utility of simulation. Two specific examples are then further discussed in depth to indicate the magnitude of cost/time savings realizable through simulation.

TABLE I. TECHNICAL PROBLEMS ENCOUNTERED DURING YAH-64 DEVELOPMENT

MAIN ROTOR:

- Vibration, Loads at High Speed with Straight Tips
- Whirl Stability
- Rotor/Canopy Interference
- Slope Landings
- Blade Root Fatigue Loads
- Pitch Housing Fatigue Loads
- Lead-Lag Damper Loads

TAIL ROTOR:

- Tab Flutter
- Inadequate Control in Right Sideward Flight
- Vortex Ring in Left Sideward Flight
- Excessive Tail Rotor Teeter in High Speed Flight
- Tail Rotor Blade (110") Near 3/rev Resonance
- Tail Rotor Fatigue Loads

DRIVE SYSTEM/PROPULSION

- Tail Rotor HP/Maximum Pitch Limit
- Engine Torsional Stability/Rotor Droop
- Engine-Out Warning
- IR Suppressor

CONTROL SYSTEM STABILIZATION:

- Hydraulic Actuator Fatigue Loads
- Directional Actuator Location
- Pitch-up at High Speed
- T-Tail Attitude
- Stabilator Schedule

AIRFRAME:

- Empennage Resonance
- Stabilator Fatigue Loads
- Tail Boom Torsion Resonance
- Tail Boom Fatigue Loads
- Pitot Location
- ADS Fatigue Loads

AVIONICS:

<u>Communications</u>

- Antenna Nulls

<u>Navigation</u>

- HARS
- Doppler
- Air Data

<u>Fire Control System Interfaces</u>

- TADS Break-Lock
- IHADSS Image Smear
- MUX Bus Control
- Recovery from Electrical System Drop-Out

<u>Crew Station Interfaces</u>

- Stores Jettison Switch
- MUX Bus Switch
- Latching Weapon Action Select Switch
- Laser Firing Safeguards
- TADS/PNVS Switching
- IHADSS Boresight Switch

<u>Weapons Interface</u>

- Hellfire Tip-Off at Launch
- Gun Impact on Electrical Bus
- Gun System Aiming
- Rocket System Aiming

TABLE I. TECHNICAL PROBLEMS ENCOUNTERED DURING YAH-64 DEVELOPMENT (CONTINUED)

SYSTEMS:

Cooling

Cockpit, Engine, Drive System, Avionics

Heating

Leakage

Deicing

Ice Detector

ORDNANCE SYSTEMS:

Flexchute Wear and Fatigue
Ammo Storage and Distribution
Gun Aiming Dynamic Stability
Dynamic Response of Wing Ordnance

POTENTIAL AH-64A TIME/COST REDUCTION WITH SIMULATION

One of the strengths of the pilot-in-the-loop simulation is the capability to address and resolve issues in a full mission environment. Rotor droop (the loss of rotor rpm in maneuvering flight) was a candidate that could have benefited considerably from simulation. Rotor droop was identified as a problem late in the program. Tests during early development did not involve aggressive maneuvers and the rotor droop was not discovered. Later, when the pilots maneuvered the aircraft briskly, it was found that the governor/fuel control system design could not cope with rotor torque demanded, thus resulting in a rotor droop. However, the determination of its impact was a difficult process since its influence was to potentially degrade mission performance in Nap-of-the-Earth (NOE) flying. To identify and confirm its potential serious consequences required extensive flight testing (about 30 - 50 flight test hours). Considering the costs of a fully instrumented flight test program, this was a very expensive process. Development of a solution to the rotor droop problem took about 6 months. Since this occurred late in the program, fixing it was extremely expensive. If a high fidelity manned simulation had been available, an expanded maneuver envelope could have been flown much earlier in the simulator and the problem most likely would have been foreseen.

The application of simulation for flight control development and handling qualities evaluation has become popular in recent years. A few areas from Apache are discussed below to indicate special considerations for simulation to be beneficial. The weapons separation and evaluation of its effects on handling qualities was an expensive part of the Apache testing. The cost included not only the flight test cost but also the cost of the weapons expended. Live weapons were to be fired and some of the weapons themselves were prototypes, thus adding to the cost. The simulator could have been very valuable in performing these evaluations not only at desired flight conditions but also with an expanded flight envelope both in sideslip and speed. A simulator would have also provided an expanded flight envelope for detailed handling qualities evaluation such as the effects of center-of-gravity (CG) shifts, and control margin availability in sideward and rearward flights. A large number and combinations of parameters could have been tried in the simulator and only the critical points selected for further flight test.

Pitch up at high speed was a problem that was noted later in the program. This necessitated the redesign of the digital automatic stabilization equipment (DASE). It took about 6 months to identify and resolve this issue. The optimization of control laws was done on the aircraft itself and took about 30 flight hours on the prototype. With a simulator, the pitch up at high speed could have been discovered early and the control laws designed more effectively and efficiently.

Problems such as these point out that the simulation model should include not only the basic aerodynamics and control laws but also should be comprehensive and accurate enough in areas such as engine models, weapons effects, control linkage representation, etc.

Surrogate Trainers: An engineering simulator could have provided tremendous cost savings to the AH-64A program in pilot transition training. Apache was the first production helicopter to use the PNVS to fly in a NOE environment. The PNVS uses forward looking infrared (FLIR) imagery to aid the crew in flying the helicopter. The TADS/PNVS was specifically designed for the Apache program and was a competitive procurement between Northrop and Martin Marietta. The Army undertook a program to train the pilots to fly the Apache with the PNVS. As part of this effort, the Army reconfigured two Cobra (AH-1S) helicopters; one with the Northrop PNVS and the second with the Martin Marietta PNVS. These aircraft served as "Surrogate Trainers". The rear seat (pilot seat) was also configured somewhat like the AH-64A. This included modifications to some of the control panels and the cyclic stick. The cockpit was blacked out with a curtain so that the pilot learned to fly without any reference to the outside world. The PNVS presented the FLIR imagery on the pilot monocle (Figure 2) with symbologies superimposed on it (Figure 3).

Figure 2. Integrated Helmet and Display Sight System (IHADSS)

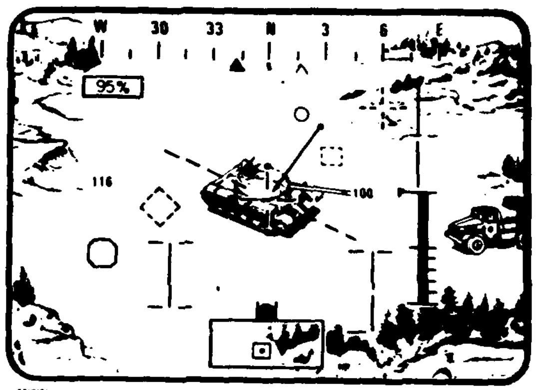

Figure 3. PNVS Imagery

Flying the helicopter with the PNVS required learning how the symbols worked and how aircraft control could be achieved with the symbology. More importantly, it was learning a new way of flying. That is, flying in an NOE environment based on cues from the FLIR imagery. This required acquisition of skills to recognize cultural features and depth cues using very subtle changes in the gray scale of the FLIR imagery. PNVS flight in this environment was workload intensive and unforgiving of errors. The PNVS training program involved 25 hours of flight of which 7 to 8 hours were dedicated to learning to fly with PNVS in daylight and become familiar with the operation of the system. The rest of the flight hours were under night conditions. The original two Cobras with the prototype PNVS were used to train the pilots until 1981. In 1982-1982, a contract was awarded to convert an additional 10 Cobras to surrogate trainers. Some of the prototype Apaches were also used for PNVS training of MDHC pilots and Army experimental pilots. In all, the training included approximately 12 MDHC pilots and 175 army pilots. The financial investment into the surrogate program was quite high - $25 million in aircraft modification costs plus the cost of about 5000 flight hours, some of which were on the prototype Apaches. An engineering simulator with a good FLIR simulation would have permitted training the pilots directly in the Apache. This would have obviated the need for the surrogate trainers thus saving as a minimum $25 million in hardware costs in addition to more effective use of flight training hours.

<u>Horizontal Stabilator</u>: The design of the horizontal stabilator was another example where simulation could have played a vital and complementary role in the design process. The stabilator design was a lengthy one involving several configurations and lasting several years. The original YAH-64 design started out with a fixed, low horizontal stabilizer mounted on each side of the end of the tail boom. Two YAH-64 vehicles (AV-02 and AV-03) were fitted in this configuration. Sikorsky's experience of trim problems on the UTTAS aircraft with a similar configuration in this time frame led MDHC to conduct a test on a modified OH-6A. A simple horizontal stabilizer was mounted at the same relative position

with respect to the main rotor as it would be on the YAH-64. It was scaled such that it would produce the required control displacement position on the YAH-64 due to the rotor downwash impingement of the horizontal stabilizer. Flight tests with the OH-6A showed that this configuration would produce excessive pitch up and unacceptable control characteristics on the YAH-64. After considerable study and analysis, a T-tail configuration was chosen, installed on the YAH-64 and the aircraft was flight tested. Some shortcomings appeared during the flight trials. One was the excessive nose-up fuselage attitude at low speeds especially in climb (Figure 4). This resulted in reduced visibility for the pilot who flew the aircraft from the rear cockpit. (The front seat is the copilot/gunner station in the tandem seating arrangement.) The pilot visibility was also affected during NOE flight.

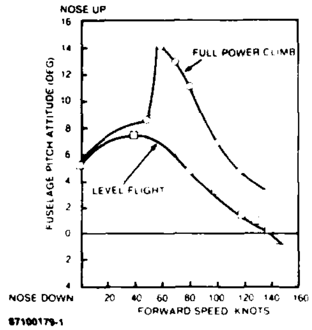

Figure 4. Fuselage Attitude with T-Tail

Another characteristic encountered was the forward trim changes required when accelerating from hover to high speed (Figure 5). Analysis and measurements revealed that contrary to expectations, the T-tail was submerged in the main rotor wake and the combination of high downwash angle and the climb angle resulted in a high negative angle of attack on the tail which produced a high download.

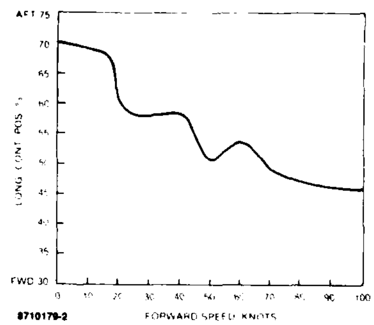

Figure 5. Longitudinal Trim Shifts with T-Tail

Subsequently, a low horizontal stabilator design was incorporated on the aircraft. The stabilator incidence was to be automatically adjusted as a function of collective pitch and speed. This enabled the aircraft to maintain constant attitude in climb and through transition from hover to high speed. This also produced the desired trim characteristics. However, the pilots still desired better visibility in descent and during landing. The automatic stabilator schedule produced only about 10 degree visibility over the nose. Hence, a manual mode option below 80 knots was also incorporated. This enabled the pilot to fly the aircraft with nose down attitude during NOE operations, descent and landing. Figure 6 shows the schedule of these developments and their phasing in relation to the contract. Full details of the empennage design are given in Reference 4.

An engineering simulator with a good visual system could have pointed out the visibility problems during design. Investigation of effects of various tail configurations could have been conducted in the simulator and the optimization of the stabilator schedule could have been achieved. It is estimated that a simulator could have saved at least one to two years in development and testing in this area.

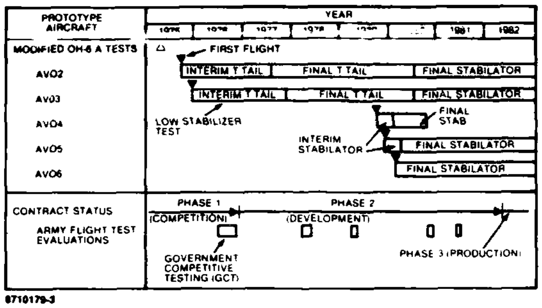

Figure 6. AH-64A Empennage Development

Cost Savings: The above examples clearly show that simulation offers a tremendous potential for cost savings. Considering that an advanced rotorcraft program employs several hundred employees, saving a year or two during development translates into cost savings of over $100 million dollars. Firm fixed price contracts with tight schedules do not permit the luxury of aircraft design by trial and error. The simulator offers an alternative capability where a wider variety of concepts and designs can be tried without actually procuring hardware thus encouraging greater innovation. More importantly, it increases the degree of confidence that the program will finish on time and the aircraft will satisfy customer requirements.

LESSONS LEARNED FOR SIMULATION

The preceding discussion has considered just a few of the Apache problem areas to provide an appreciation for potential cost and time savings through the use of man-in-the-loop simulation. This section will consider what needs to be done to tap this potential on future programs.

The marketing aspect of a simulator has been well recognized by aircraft companies. However, to fully exploit the engineering capabilities, various organizations within the company must do significant planning and coordination so that the simulator is used as an integral part of the design, development and test processes. This means well defined requirements for simulation must be generated very early in the program. These requirements must reflect those for the aircraft such that the simulator truly represents the aircraft.

Since the simulation fidelity is only as good as the mathematical models used, efforts must be made to develop very accurate math models for simulation. Better analytical tools and computational methods are now available to rotorcraft design engineers to develop more accurate math models than what was possible during the Apache development. Advances in computing technology have made computational resources affordable for real-time simulation. Experience with problems such as rotor droop indicates that it is important to include engine dynamics and other effects that in the past have been ignored in real-time simulation. Incorporation of these effects will need innovative approaches to modeling so that significant effects can be included without overloading computational systems.

Man-machine interface is a very strong area for simulation application. This requires that the cockpit functionality be a faithful replication in all respects. This includes field of view and visual obstructions. To load the pilot as in real world environment, the studies must be conducted under simulated mission scenarios. Though not discussed in this paper, some of the man-machine interface problems were discovered on the Apache under emergency flight conditions. Hence, engineering simulation should also include malfunctions so that all displays, switches, procedures and sequences can be rigorously evaluated. Traditionally, engineering simulators ignore malfunctions and this philosophy must change. Consideration should also be given to simulation of noise and vibration, because of their effects on pilot fatigue and mission performance.

As evident from the discussion on the surrogate training and horizontal stabilator design a good visual and sensor simulation is a must and well worth the investment.

Transportability of software between simulator, hot bench and aircraft must be required on future simulators. This will permit efficient development and debugging of operational software and free the aircraft for flight tests. This will avoid duplication of software efforts between design and simulation organizations and also provide better configuration control. Figure 7 shows how simulation could be used in aircraft development.

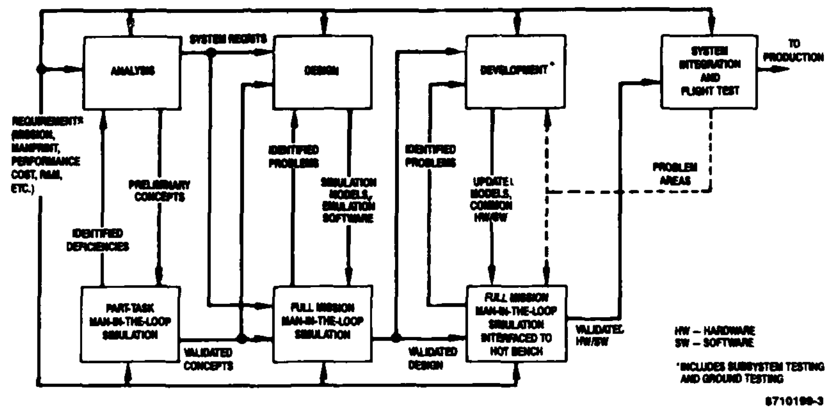

Figure 7. Simulation Support to Helicopter Development

CONCLUSION

This paper has highlighted some aspects of the AH-64A Apache helicopter development history. A few problem areas were discussed to point out the potential for cost and time savings through use of engineering simulation. A modern full mission engineering simulator when used effectively could provide cost savings of several millions of dollars, and could reduce development and flight test by at least a year or two. These estimates are subjective, but are based on the experience of those who were deeply involved in the Apache program. An equally important contribution of simulation would be to provide a higher degree of confidence that the aircraft program will finish on time. In the opinion of experts, the degree of confidence will be about 10-60 percent without simulation and about 90 percent with simulation.

ACKNOWLEDGMENT

This paper was the result of stimulating discussions with a number of MDHC personnel. Special thanks to Messrs. Ken Amer, Ed Currier, Steve Hanvey and Skip King for freely sharing their experience and insight.

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SYSTEMS ANALYSIS AND SIMULATION TECHNIQUES,- ESSENTIAL TOOLS FOR BALANCED COMPLEX WEAPON SYSTEM DESIGNS IN TERMS OF PERFORMANCE AND COST

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SUMMARY

In line with the speed of overall technical evolution, the requirements for weapon systems are steadily increasing. The required levels of performance lead to complex and expensive technical solutions. The resulting cost of the single weapon system, together with the demand for sufficient quantities, increasingly conflicts with natural budget limitations.

For an effective cost control, the cost driving requirements have to be identified and analysed before the weapon system design begins. The major tool for this task is an integrated analysis of technical parameters, operational aspects and life cycle cost based on mathematical simulation, tailored to the amount of available information.

This integrated analysis leads to recommendations for the single weapon system and the necessary quantities for given scenarios. By involving the customer early enough, the staff requirements for the weapon system can then be influenced in such a way, that the design can be balanced in terms of performance and cost.

1. THE PROBLEM AND HOW TO SOLVE IT

In view of the rapidly growing military threat, the requirements for weapon systems to counter that threat are steadily increasing. This results in increasing weapon system complexity and cost. Due to natural constraints of defence budgets the cost increase for the single weapon system leads to a decrease in the quantities that can be procured with the available funds (figure 1). E.g., German Luftwaffe can afford just one TORNADO to replace about two F-104 Gs. In return the TORNADO has a higher combat performance than its predecessor.

That relation shows one of the main problem areas for future weapon systems:

High complexity and low quantities
vs. less complexity and higher quantities.

The necessary level of complexity and, thus, the cost of a weapon system are determined by the requirements. The requirements, however, are driven by the threat. Due to decisions already made, a weapon system's life cycle cost is ┌about 50 % at the point of establishment of the requirements (figure 2). Therefore, the analysis of threat and requirements becomes very essential before the design begins.

┌fixed to a level of

This analysis should cover the following major areas:

- technical parameters
- operational aspects
- cost (life cycle cost).

Furthermore, it has to be an integrated analysis in order to take care of the interrelationships between the various parameters. The big amount of data for quite a number of alternatives as well as the limited time frame, which normally is left for decisions, requires the use of automated data processing. The various parameters are linked together by means of mathematical simulation. The algorithms have to be specially tailored reflecting the availability of information in an early project state. The aim should be, as shown in figure 3, to work out a 'balanced' weapon system design in terms of performance and cost early enough, in order to support the setting up of the staff requirements accordingly.

Figure 4 illustrates the procedure for achieving this aim. First of all, the threat has to be analysed and initial requirements for a weapon system to counter that threat have to be set up. Simultaneously, the possible scenarios, in which the weapon system will be operated, have to be defined. Both, initial requirements and scenarios, form the design environment for the further analysis. As a starting point for parameter variation a basic technical solution then has to be established in terms of design and cost. From this basis the above defined aim can be reached by the following two steps:

1st Step: PARAMETER ANALYSIS

The parameter analysis identifies the design and cost driving parameters and quantifies their effect on the weapon system's

- performance and
- cost (life cycle cost).

2nd Step: FLEET EFFECTIVENESS ANALYSIS

The fleet effectiveness analysis consists of an integrated analysis of

- weapon system performance,
- operational aspects, and
- life cycle cost

by integrating the combat performance of the single weapon system into the otal fleet.

For both steps life cycle cost are based on peace time operation, since peace time operation determines those costs the customer has to take, in order to have the weapon system ready for its designed purpose.

The two step analysis finally results in recommendations for

- (single) weapon system and
- quantity (fleet size).

2. PARAMETER ANALYSIS

As detailed in figure 5, the parameter analysis mainly consists of three areas:

- design analysis
- operational analysis
- cost analysis.

The design analysis covers

- configuration
- performance
- equipment/weapons.

The operational analysis includes

- mission performance
- survivability
- operational readiness.

Via both analyses the design driving parameters can be identified and quantified by using parameter variation. The cost analysis will then lead to quantification of those parameters in terms of life cycle cost.

Combat simulation based on the technical and operational data shows the combat performance of the single weapon system expressed in

$$\text{Exchange Ratio} = \frac{\text{opponent losses}}{\text{own losses}} .$$

Exchange Ratios are evaluated for the 1:1 combat situation and for the 1:>1 combat situation to cover the multi target case.

Combined with the cost sensitivity of the relevant parameters, the exchange ratios define the achieved level of combat performance and its cost. Thus, the parameter analysis can be used to optimise the (single) weapon system in terms of performance and cost.

Figure 6 shows some typical parameters for a fighter aircraft and the respective tools for their variation. In the early project state technical parameters can be analysed by a scaling ("sizing") model combined with performance calculation. Typical design parameters for a fighter aircraft are e.g.

- wing loading
- thrust to weight ratio
- design mission parameters.

The analysis of the operational parameters should be performed by operation simulation.

One essential part of this analysis is the combat simulation incl. simulated combat with the pilot in loop, if possible.

The pilot in loop capability of the simulation gives additional benefit by providing better information to the customer on the weapon system's behaviour. The results of combat simulation of course depend on the relevant parameters of the opposing aircraft,

such as performance, operational parameters, and quantity. The latter is an important datum for the necessary multi target capability and the development of special combat tactics for the own weapon system.

Life cycle cost analysis based on peace time operation may prove to be a difficult task due to the limited amount of data in the early project state. It may happen, that existing life cycle cost models do not respond properly to the relevant parameters. In that case the following procedure can lead to more satisfying results:

The basic technical solution (see figure 4) has to be costed in detail for the different programme phases (development, procurement, operation) reflecting the complexity of the weapon system's design. The variation of design parameters leads to various scaled point designs, similar to the basic technical solution in terms of configuration, complexity, equipment, engine etc., but bigger or smaller in size. Therefore, those scaled point designs can be costed by CERs (Cost Estimating Relationships) which mainly take care of the scaling in size. Some of the equipment, e.g. mission avionics, weapons, pilot equipment etc., remain constant, while the bigger portion of the weapon system will vary in terms of mass. From the latter portion a certain part will vary steadily, e.g. the airframe, while - in reality - the other part will change in steps, e.g. equipment like electric power generation, engine etc. In a simplifying approach, this equipment can be regarded as 'rubber' equipment, i.e. equipment with steadily increasing or decreasing performance and mass. Thus, the effect of cost driving parameters can be evaluated by costing the complete scaled weapon system instead of just costing the direct effects of the parameter variation, which normally requires a higher effort and more specialised cost models.

Figure 7 shows as one example the change of exchange ratios for various design driving parameters. For a fighter aircraft the increase of turn rate, which is a favourable solution for the short range air combat, does not lead to significant improvements for the medium range air combat. The increase of specific excess power (SEP) does improve the exchange ratio but is limited due to physical constraints of propulsion technology. Best results in the medium range air combat can be achieved by reducing the radar signature or by increasing the radar detection range, i.e., very simply, the advantage is on the side of that aircraft, which detects its enemy before it is detected itself.

After identifying and quantifying the design driving parameters in terms of combat performance, the cost resulting from the parameter variations have to be evaluated. For specific excess power (SEP) and turn rate the relative life cycle cost of the weapon system are presented in figure 8 as a second example. In addition, this figure shows also the relative life cycle cost for any combinations of those two parameters. The marked area reflects the limits for both parameters, which from a technical point of view are regarded as realistic and achievable with justifyable effort. The points of intersection between the curves represent the scaled point designs used for life cycle costing.

These two examples, which are presented here, illustrate the result of the parameter analysis. The variation of combat performance in terms of exchange ratio and its cost for various design driving parameters will be evaluated and provide the necessary information to optimise the (single) weapon system in terms of performance and cost.

3. FLEET EFFECTIVENESS ANALYSIS

The ideal solution for the customer would be to procure and operate the optimised weapon system in required quantities. As shown in figure 9 this desirable solution is very often not feasible. The optimised technical solution and the necessary fleet size to counter the threat in terms of quality and quantity increasingly is not affordable for the customer. Therefore, a tool is required to balance out the optimum fleet performance as a compromise between the single weapon system's combat performance and the required quantity of systems.

This tool is the fleet effectiveness analysis and the measure for the fleet performance is defined as Fleet Effectiveness

$$= \frac{\text{No. of opponent losses during conflict}}{\text{life cycle cost (peace time operation)}} \quad \text{(figure 10).}$$

The fleet effectiveness analysis combines

- combat performance
  (exchange ratios of the single weapon system), and
- operational analysis
  (sorties per day and aircraft)

to evaluate the necessary fleet size to counter the threat in terms of quality and quantity for relevant scenarios, i.e. for different combat situations, performance levels and quantities of opposing aircraft etc. This 'minimum' fleet size will vary for different design driving parameters and different scenarios. By including

- cost analysis,

The life cycle cost (peace time operation) of the various 'minimum' fleet size solutions can be identified. Thus, the fleet effectiveness analysis results in recommendations for weapon system and fleet size.

Figure 11 shows the possible number of weapon systems/aircraft that can be developed, procured and operated for a given life cycle cost budget (LCC = 1.0 = const.) and various specific excess power (SEP) and turn rate combinations. The marked area corresponds to the one in figure 8 and includes those values, that are regarded as achievable with justifyable effort.

Figure 12 illustrates the increase of the 'minimum' fleet size and its life cycle cost with growing opposing fleet size (defined opposing aircraft) for different SEP and turn rate combinations of the Blue (= own) aircraft. For a given life cycle cost budget (LCC = 1.0 = const.) the 'high' performance alternative of the Blue aircraft can neutralize a bigger fleet of opposing aircraft than the 'low' performance alternative. I.e., the larger quantity of 'low' performance aircraft for that given life cycle cost budget (see figure 11) obviously cannot outbalance the shortfall in manoeuvre performance.

If the fleet size Red moves further to bigger numbers the compensation of that quantity by further increasing the Blue aircraft's manoeuvre performance gets technically difficult. The right borderline of Blue SEP/turn rate combinations reflects the above mentioned limits as of figure 8 and 11. Therefore, only an equivalent increase of the 'minimum' fleet size Blue, and thus, of the life cycle cost budget, can counter the threat. For a large opposing fleet size this leads to solutions beyond the available funds.

In that case, other technical and/or operational solutions are required to reduce the 'minimum' fleet size Blue, because aircraft quantity is one of the main life cycle cost drivers for the total weapon system.

Figure 13 shows one of the possible solutions concerning the operational area: an improvement of the sortie rate Blue leads to a reduction of the required 'minimum' fleet size. This sortie rate improvement can be achieved e.g. by less maintenance and repair effort (MMH/FH), by lower turn around time or by improvement of the weapon system's reliability (MTBF). The trend of the curve illustrates, that further reductions of the 'minimum' fleet size can only be reached by an increasing effort to raise the sortie rate. The achievable level of sortie rate, however, is limited by the state of technology.

Besides the operational area there are further technical solutions to reduce the 'minimum' fleet size. As already presented in the parameter analysis there are some other possibilities to increase the combat performance, e.g.

- increase of radar detection range
- reduction of radar signature.

The first one means to improve one of the main sensors of the aircraft and not the airframe performance and is an active measure. The second one is a passive measure and mainly covers design and configuration of the airframe. Both solutions lead to considerable reductions of the 'minimum' fleet size, and thus, the life cycle cost.

The examples given above only show a small portion of the total fleet effectiveness analysis. Nevertheless, they are presented here to demonstrate the results that can be achieved and their use for the weapon system design in order to balance (single) weapon system performance, fleet size, and life cycle cost.

4. RECOMMENDATIONS

The final recommendations concerning the design process of a complex weapon system are summarised in figure 14.

In order to meet the highly integrating task of designing a complex weapon system and to take care of the various interrelationships between the different design driving parameters, the integration and harmonization of all available tools is required. In addition, the staff departments involved should be organized respectively in order to give optimum support to the analyses and to improve the flow of information.
The areas concerned are:

- systems analysis
- simulation techniques.

It is essential, that the tools can be used in the early state of the project and that the results are provided quickly enough to influence outstanding decisions. The incorporation of all relevant aspects (technical, operational, cost) safeguards an overall 'balanced' design of the weapon system.

Since one of the main influences on the weapon system's life cycle cost comes from the requirements, it is also essential to involve the customer early enough and to provide guidelines for the final set-up of the requirements.

In that respect, parameter analysis and fleet effectiveness analysis are the necessary tools for the

- limitation of cost driving requirements to the extent necessary and the
- substitution of cost driving requirements by complementary and less costly ones.

<u>Reference</u>

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(Jahrestagung der DGLR, Bonn - Bad Godesberg, 30.09. - 02.10.85)

FIGURES

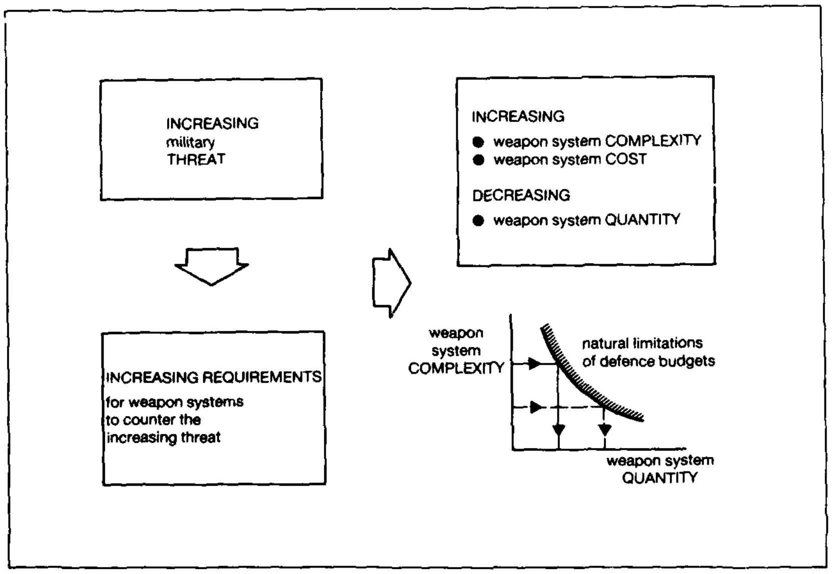

Figure 1: THE PROBLEM:
Increasing Requirements → Increasing Cost

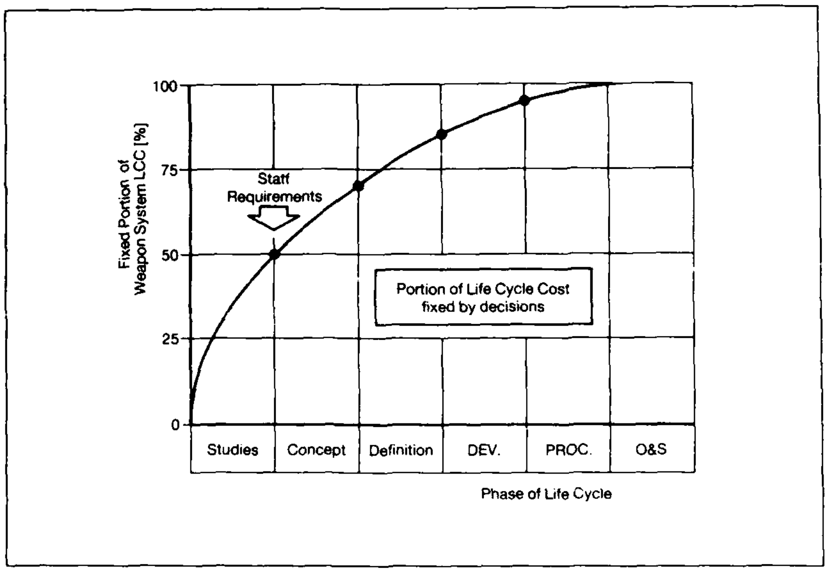

Figure 2: THE PROBLEM (cont'd):
Increasing Effort to influence Cost with proceeding Life Cycle

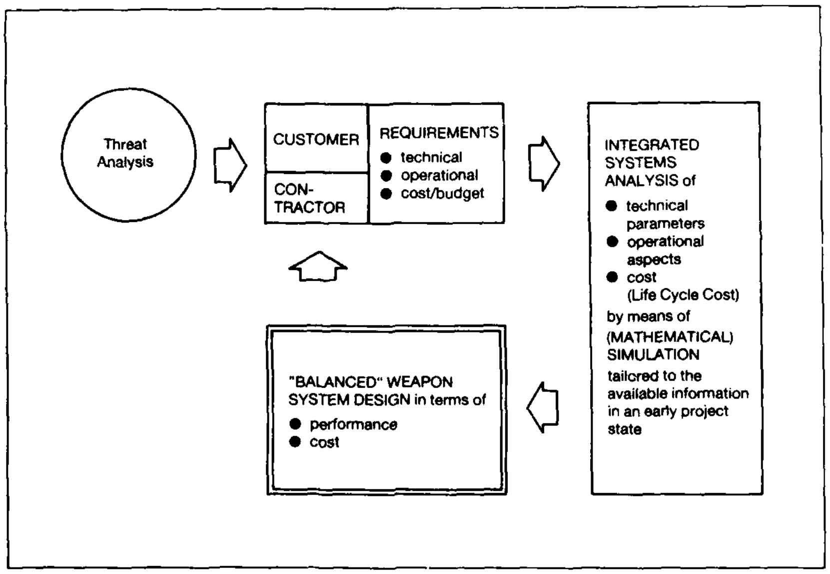

Figure 3: THE AIM:
'Balanced' Weapon System Design
(performance & cost)

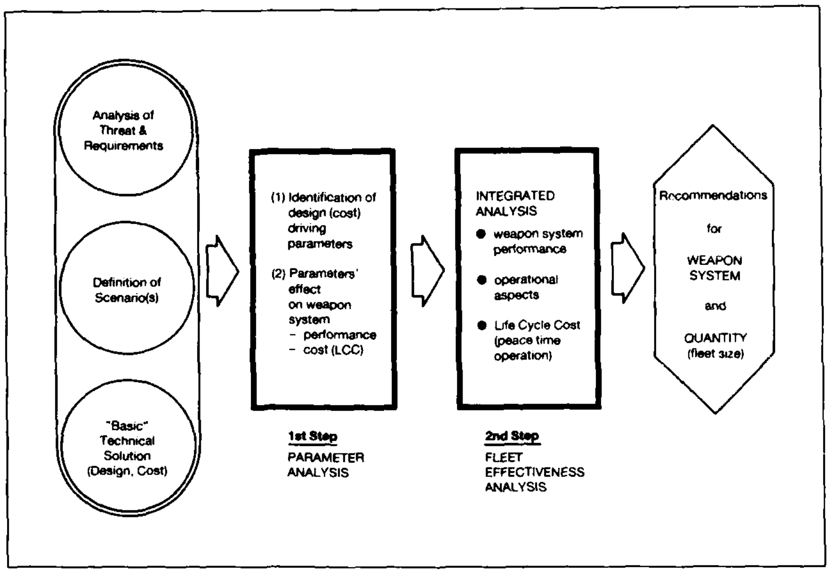

Figure 4: THE PROCEDURE:
Parameter Analysis and Fleet Effectiveness Analysis

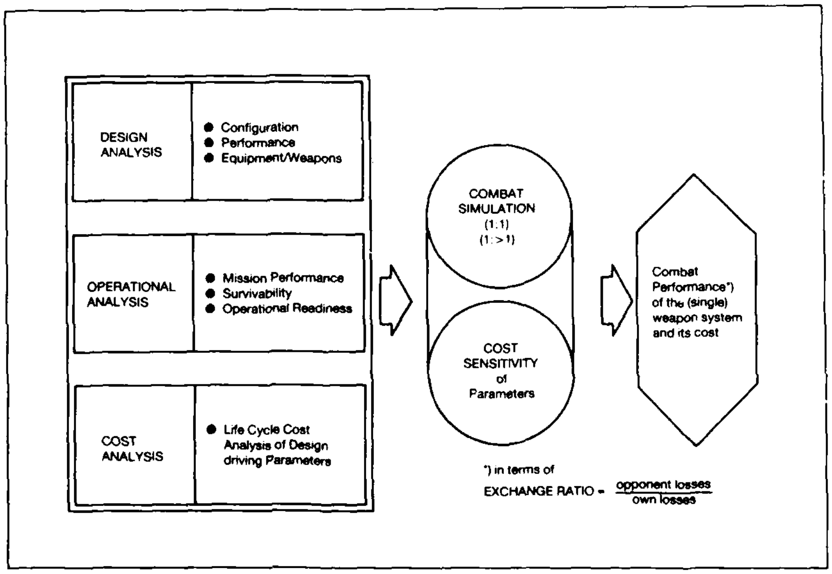

Figure 5: PARAMETER ANALYSIS:
Optimisation of the (single) weapon system

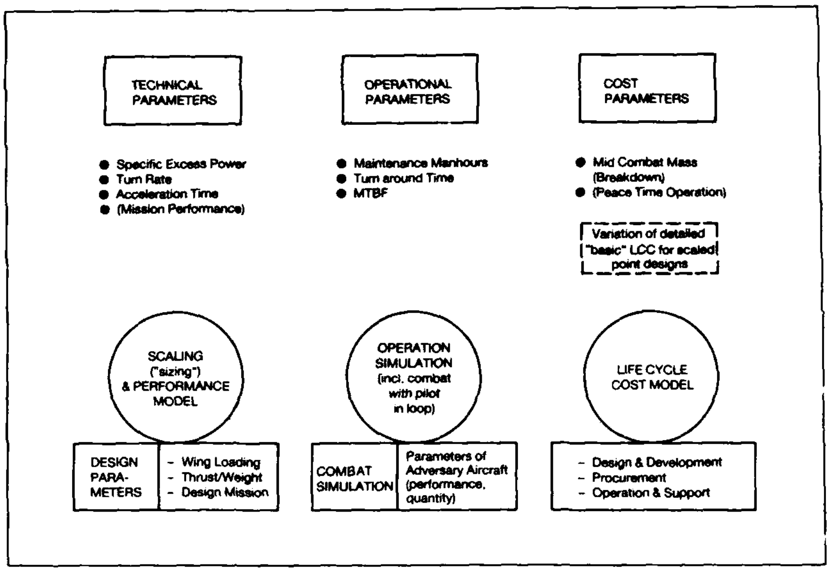

Figure 6: TYPICAL PARAMETERS
Example: Fighter Aircraft

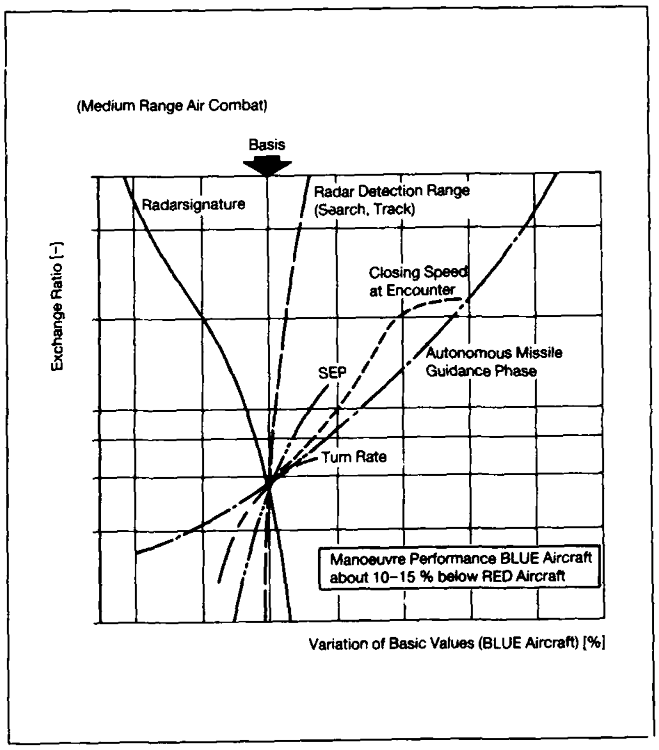

Figure 7: PARAMETER ANALYSIS
Example 1: Exchange Ratios vs. Design Driving Parameters

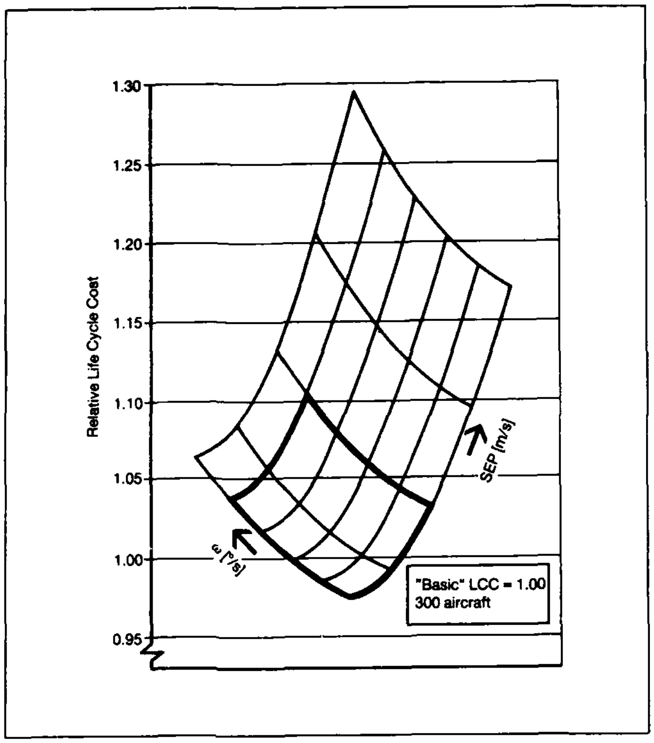

Figure 8: *PARAMETER ANALYSIS*
Example 2: LCC vs. SEP and Turn Rate (ω)

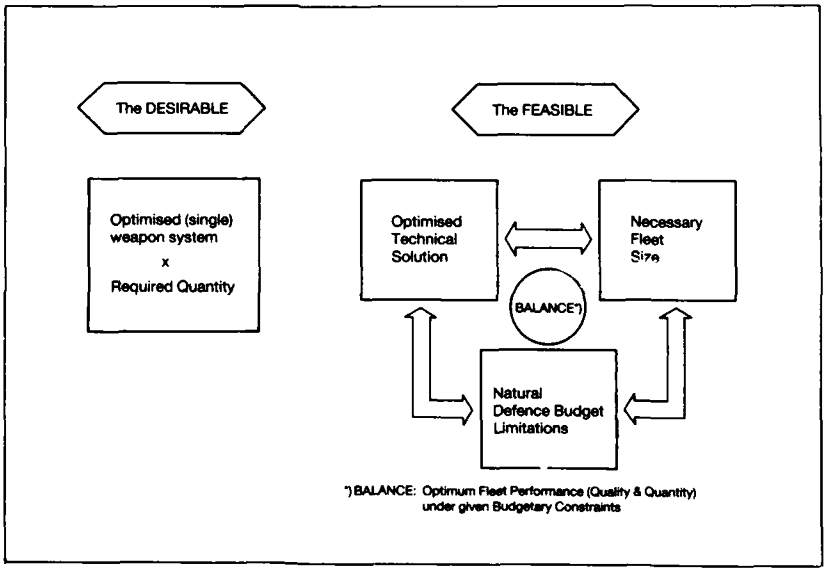

Figure 9: FLEET EFFECTIVENESS ANALYSIS:
From the DESIRABLE to the FEASIBLE

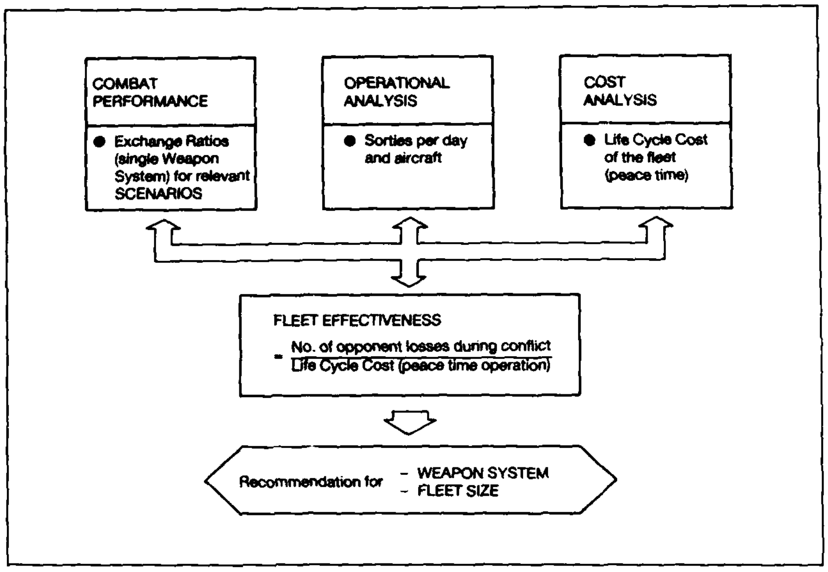

Figure 10: FLEET EFFECTIVENESS ANALYSIS (cont'd):
Balance of weapon system, quantity and cost

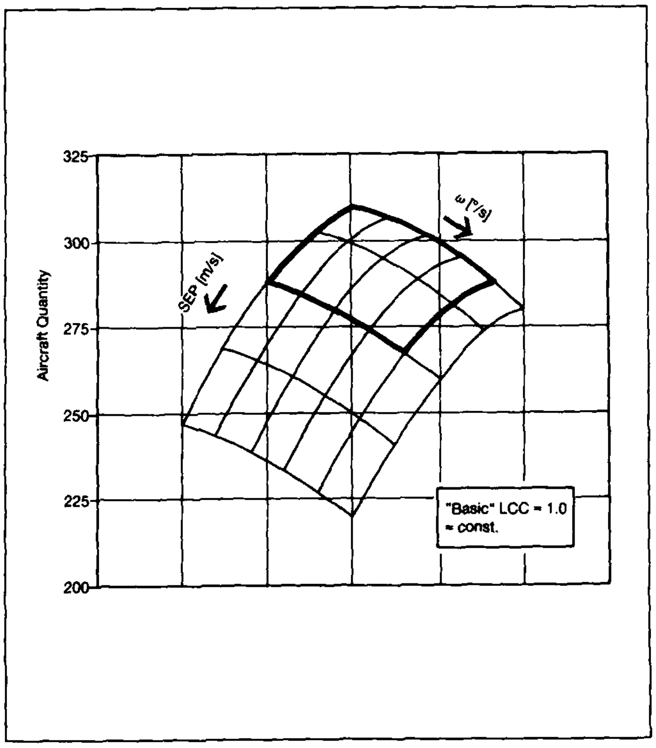

Figure 11: FLEET EFFECTIVENESS ANALYSIS
Example 1: Fleet Size vs. SEP and Turn Rate (ω)
(LCC = const., i.e. given budget limitation)

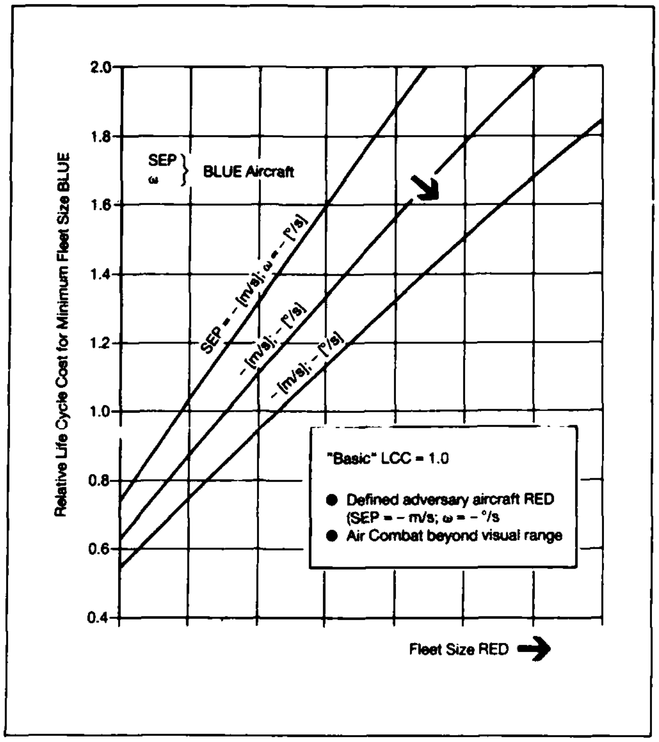

Figure 12: FLEET EFFECTIVENESS ANALYSIS
Example 2: LCC vs. Opposing Fleet Size for various SEP/Turn Rate (ω) Combinations

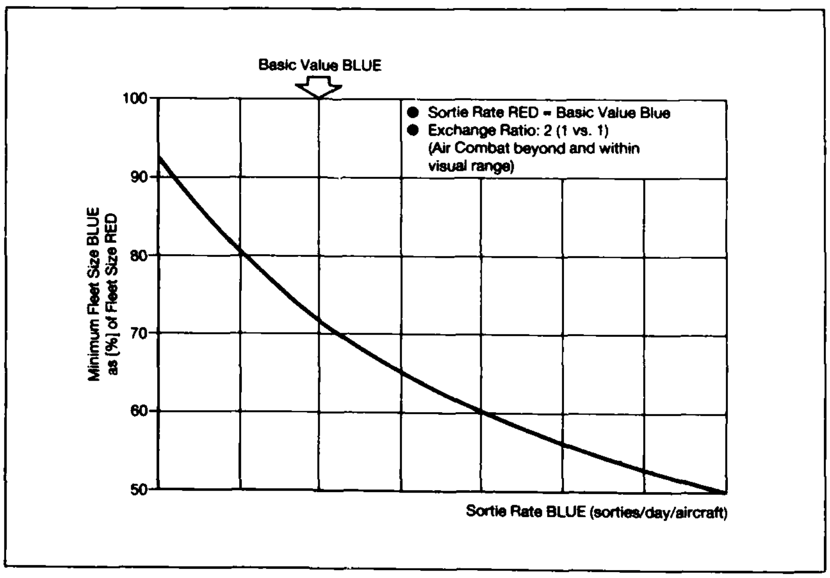

Figure 13: FLEET EFFECTIVENESS ANALYSIS
Example 3: Minimum Fleet Size Blue vs. Sortie Rate Blue

- Design of complex Weapon Systems as a highly integrating task requires the Combination and Harmonization of all avaible tools and adequate staff organisation
    - SYSTEMS ANALYSIS
    - SIMULATION TECHNIQUES

  at a rather early state of the project

  > Incorporation of all relevant aspects (technical, operational, cost) into the Weapon System by maintaining an
  > - OVERALL "BALANCED" DESIGN

- Involvement of the customer is required to set up guidelines for the Weapon System requirements early enough

  > - Limitation of cost driving requirements to the extent necessary
  > - Substitution of cost driving requirements by complementary and less costly ones

Figure 14: SUMMARY & RECOMMENDATIONS

L'APPORT DE LA SIMULATION

DANS LE DEVELOPPEMENT DES AIRBUS

par
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0. SOMMAIRE -

L'accroissement constant de la complexité des systèmes et leur intégration de plus en plus étroite à bord des avions modernes entraînent en contrepartie une augmentation continue du volume des tâches associées aux études de définition d'une part et à la validation de l'intégration de ces systèmes sur avion d'autre part.

La simulation constitue une des réponses à ces contraintes dans la mesure où elle permet, à travers les possibilités d'anticipation qu'elle comporte :

- de définir en détail l'architecture et les principes des systèmes dans leur ensemble sans répercussions notables sur l'industrialisation.
- de valider et mettre au point les réalisations qui découlent de ces définitions, suffisamment tôt dans le déroulement du programme pour autoriser les ajustements nécessaires sans répercussions trop importantes en coût et délais sur le développement.

Pour mener à bien ces différents types de tâches, l'AEROSPATIALE a mis en oeuvre depuis plus de 20 ans des outils de simulation variés :

- simulateurs d'études prospectives, orientés vers les études à long terme, axées en particulier sur l'aménagement du poste et l'ergonomie des commandes et des informations.
- simulateurs de développement, pour la définition détaillée des systèmes attachés à un programme déterminé.
- simulateurs d'intégration, pour la validation, la mise au point et l'optimisation des performances de ces systèmes dans leur forme avionnable.

1. INTRODUCTION -

L'évolution constante des technologies existantes ainsi que l'apparition de potentiabilités nouvelles dans ce domaine permettent une avancée continue dans la recherche de l'amélioration des performances des matériels aéronautiques.

Cette recherche est notamment axée vers l'économie d'exploitation et la sécurité du vol : il n'est donc pas question de la remettre en cause.

Il n'en reste pas moins cependant que cette progression des performances s'accompagne en retour d'une complexité croissante des systèmes chargés de réaliser des objectifs opérationnels de plus en plus ambitieux.

Cette évolution a ainsi fait rapidement apparaître la nécessité pour l'avionneur de disposer de moyens efficaces permettant aussi bien la poursuite d'études détaillées de définition que la vérification de l'intégration de ces fonctions dans l'avion.

L'AEROSPATIALE s'est en fait engagée dès 1962 dans la voie de la simulation en vue de l'étude et de l'intégration de la fonction Atterrissage Automatique sur "CARAVELLE".

Par la suite, l'importance croissante prise par les systèmes, leur intégration de plus en plus poussée entre eux et avec l'avion ainsi que l'expérience positive des premières installations ont confirmé de façon constante la nécessité de mettre en oeuvre les moyens de simulation de plus en plus puissants et nombreux.

2. PHASES D'UTILISATION DE LA SIMULATION DANS UN PROJET D'AVION NOUVEAU -

Bien que l'utilisation de la simulation dans l'étude et le développement d'un avion nouveau soit continue, on peut distinguer trois phases qui se différencient principalement par la période où elles se situent et les objectifs à réaliser.

2.1. Simulateur d'étude prospective :

Dans cette phase, la simulation est orientée à relativement long terme (7 à 8 ans) et vers une application tous programmes.

Il s'agit là d'une phase d'autant plus importante que le délai fixé entre la date de lancement d'un programme et celle prévue pour l'obtention du certificat de navigabilité est très courte et que, d'ailleurs, de multiples raisons plaident pour chercher à le réduire.

L'objectif est d'étudier l'application de principes nouveaux ou de technologies nouvelles aux équipements et systèmes de l'avion et de rechercher les avantages qu'on peut en retirer sur les plans :

- de l'amélioration du dialogue Homme-Machine
- de l'amélioration du produit en termes de performances, coût, masse, sécurité, facilité de maintenance.

Les équipementiers sont, bien entendu, associés à cette phase de travail mais c'est à l'avionneur qu'il incombe d'assurer l'intégration de l'ensemble. Aussi doit-il participer activement à la réalisation de certains équipements expérimentaux et, à travers ces travaux, acquérir une une certaine maîtrise des technologies nouvelles, tout au moins au niveau de leur utilisation.

2.2. <u>Simulateur de développement</u> :

Dans cette phase, la simulation est orientée à moyen terme (3 ou 4 ans) et vers un projet bien déterminé. Au moment où la décision de lancer un nouveau programme est prise, une sélection est faite, parmi les recherches prospectives en cours, de celles qui peuvent être appliquées au nouvel avion :

- technologies réellement disponibles
- niveaux de risques industriels admis
- maîtrise des nouvelles technologies
....

L'utilisation de la simulation dans cette phase a pour but d'aller au-delà des études spéculatives menées jusque là et d'acquérir une définition réellement détaillée des équipements et des systèmes retenus pour l'avion. Le passage de la phase étude prospective à la phase développement s'effectue en réalité avec un large recouvrement dans le temps, généralement lié au délai de mise en place du simulateur de développement.

Pour apporter au nouvel avion le maximum d'améliorations et dans le souci de tenir compte au maximum des contraintes propres des utilisateurs, les compagnies clientes et les autorités de certification sont associées étroitement, à travers des présentations fréquentes, aux études faites lors de cette phase.

2.3. <u>Simulateur d'intégration</u> :

Dans cette phase, la simulation est orientée vers le court terme (2 ans) et elle est spécifique du programme en cours.

Les études effectuées lors des phases antérieures ont conduit à l'élaboration de spécifications détaillées d'équipements et de systèmes dont la réalisation est confiée à différents équipementiers.

Quels que soient le sérieux de ces industriels, les moyens qu'ils mettent en oeuvre, la valeur de leurs équipes, aucun d'entre eux n'a la capacité de vérifier le comportement des équipements qu'il réalise lorsque ceux-ci sont intégrés à d'autres équipements d'un même système et, encore moins, aux autres systèmes et à l'avion. Il est donc de la responsabilité de l'avionneur, qui seul en a la possibilité, de le faire.

Après une première phase sur banc partiel, les équipements et systèmes à valider et à certifier sont couplés à un simulateur dont le rôle est de fournir un environnement aussi complet et représentatif que possible de l'avion et par là même de reproduire le plus fidèlement possible les conditions de son utilisation opérationnelle.

Dans la période qui précède le premier vol de l'avion, l'objectif est alors triple :

- vérifier que les équipements sont conformes aux spécifications,
- vérifier que les spécifications traduisent bien les objectifs opérationnels visés,
- dans les cas où des anomalies apparaissent, les analyser et rechercher les définitions nouvelles permettant de les corriger.

Dans une deuxième période qui correspond au programme d'essais en vol, l'apport de la simulation est double :

- chaque vol de l'avion est au préalable répété sur simulateur afin :
  - d'une part de valider le standard des équipements qui seront montés à bord de l'avion
  - d'autre part de mettre au point en compagnie de l'équipage l'ensemble des manoeuvres prévues par le programme d'essai.
- le maximum d'essais de certification est effectué sur les simulateurs avec la participation des différentes autorités de certification : il s'agit non seulement d'alléger le programme d'essais en vol mais aussi de ne pas affecter la sécurité des vols (présentation de certains cas de pannes critiques par exemple).

Au-delà du Certificat de Navigabilité enfin, l'exploitation de ces simulateurs est poursuivie pendant plusieurs années pour assurer le suivi des problèmes rencontrés en exploitation et le développement de versions nouvelles, consécutives à des demandes particulières de la part des compagnies clientes.

3. L'EXEMPLE DU PROGRAMME A 320 -

On retrouve sur ce programme les différentes phases caractéristiques qui viennent d'être décrites schématiquement.

Il est à noter que ce programme se caractérise par des objectifs particulièrement ambitieux, tant par le volume d'éléments novateurs introduits dans de nombreux domaines que par la brièveté des délais impartis à son développement.

3.1. Etudes prospectives :

Cette phase s'est en fait appuyée sur l'utilisation de 3 simulateurs :

- simulateur EPOPEE (phase 2)
- simulateur de l'A 300 n° 3
- simulateur "avion civil" du CEV d'ISTRES.

Le simulateur de l'A 300 n° 3 a été mis en service pour assurer le support de l'expérimentation en vol sur l'A 300 n° 3 du système de commandes de vol électriques associé à des manches latéraux.

L'A 300 n° 3 est, rappelons-le, l'avion d'expérimentation d'AIRBUS INDUSTRIE.

Le simulateur "avion civil" du CEV d'ISTRES a été utilisé en partie pour décharger le simulateur EPOPEE mais aussi pour confirmer par l'utilisation de son mouvement cabine un certain nombre de points ayant trait à la pilotabilité (le simulateur EPOPEE étant à base fixe).

Les études réalisées sur ces différents moyens sont résumées dans le tableau ci-dessous :

MOYEN	ETUDES
SIMULATEUR EPOPEE	- Symbologie des écrans de pilotage, PFD et ND - Symbologie des écrans CONTROLE/ALARMES, SD et WD - Pilotabilité par manche latéral - Lois de pilotage CDVE - Lois de pilotage moteurs - Interface homme-machine - Indicateurs para-visuel ou tête haute - Présentation aux compagnies clientes
SIMULATEUR A300 n° 3	- Définition et validation du système expérimental de CDVE (1ère étape) - Support des essais en vol de ce système
SIMULATEUR "AVION CIVIL" CEV ISTRES	- Lois de pilotage CDVE (compléments) - Influence du mouvement avion sur le pilotage

3.2. Phase de développement :

Le simulateur de développement A 320 a été mis en service en Mars 1985 après reconversion du simulateur A 300 n° 3. Dans les études effectuées sur ce simulateur et résumées dans le tableau ci-dessous, on retrouve celles commencées sur les simulateurs d'études prospectives mais avec comme objectif cette fois d'acquérir une définition détaillée des systèmes nouveaux concrétisée dans les spécifications soumises aux équipementiers :

SIMULATEUR DE DEVELOPPEMENT	- Symbologies des écrans de pilotage, PFD/ND - Symbologie des écrans contrôle/alarmes SD/ND - Pilotabilité par manche latéral - Lois de pilotage CDVE - Logiques de priorité pilote/copilote - Lois de pilotage moteurs - Validation du système expérimental de CDVE sur avion A300 n° 3 (2ème étape) - Support des essais en vol de ce système - Indicateur paravisuel - Présentation aux compagnies clientes - Présentation aux autorités de certification

L'exploitation de ce simulateur s'est prolongée jusqu'en Décembre 1986, tout d'abord pour as-

surer le support des essais en vol de l'A 300 n° 3 (jusqu'en Septembre) puis pour finaliser les spécifications des logiciels des calculateurs de CDVE.

3.3. Phase d'intégration :

Par rapport à l'A 310, le programme A 320 a donné lieu à une augmentation sensible des travaux d'intégration,
- du fait de l'apparition de systèmes nouveaux et critques :

  . commandes de vol électriques (CDVE)
  . contrôle électronique des moteurs (FADEC)

- du fait également qu'un niveau d'intégration plus poussé était recherché :

  . couplage au système de génération électrique
  . couplage aux ADIRS

Or l'expérience du programme A 310 a montré que les deux simulateurs d'intégration qui avaient été mis en service avaient à peine suffi à faire face à l'ensemble des tâches de la phase d'intégration.

Toutes ces raisons ont conduit à prévoir pour l'A 320 la mise en service de trois simulateurs :

- les deux premiers sont en service depuis Mai 1986
- le troisième (affecté plus spécialement aux travaux relatifs au FMS) est opérationnel depuis Mars 1987.

Pour des raisons évidentes de coût et de charges d'étude, ces simulateurs ont en commun un maximum d'éléments de définition et de constituants matériels :

. calculateurs
. interface
. logiciel de simulation
. interconnexion de l'ensemble des systèmes

De ce fait, de nombreux essais peuvent être réalisés indifféremment sur l'une ou l'autre des installations, ce qui permet une plus grande souplesse dans la planification des essais.

Chaque simulateur présente toutefois des caractéristiques particulières qui le rendent plus apte à la réalisation de certains essais :

- le simulateur n° 1 est le seul qui puisse être couplé au banc général d'essais du système hydraulique et de la partie mécanique des commandes de vol (IRON BIRD) : c'est l'installation la plus appropriée aux essais d'intégration du système de commandes de vol.

- le simulateur n° 2 est le seul qui comporte une simulation de la totalité des systèmes annexes de l'avion (pressurisation, conditionnement d'air, carburant, portes, oxygène ...) : c'est lui qui permet d'évaluer la totalité des fonctions du système de contrôle et d'alarme (ECAM).

- le simulateur n° 3 comporte des possibilités de couplage moindres et une définition plus simplifiée que les deux premiers : il est, comme on l'a vu, plus particulièrement affecté aux essais du système de navigation et de gestion du plan de vol (FMS).

Du point de vue capacité d'intégration des systèmes essentiels, le simulateur n° 1 qui est de ce point de vue le plus complet peut être couplé aux systèmes avion réels suivants :

- génération hydraulique
- génération électrique (à temps partiel)
- systèmes de commandes de vol
- systèmes de contrôle automatique du vol
- systèmes de contrôle de la poussée
- système de navigation et de performances
- système de freinage et d'orientation de roue avant
- instruments de pilotage et navigation (EFIS)
- instruments de contrôle systèmes et alarmes (ECAM)
- système anémo-inertiel (ADIRS) (à temps partiel)

L'ensemble de ces systèmes représente plusieurs centaines d'équipements réels dont :

- 32 calculateurs de 16 types différents
- 21 servocommandes de 5 types différents
- 8 servomoteurs (hydrauliques et électriques)
- la totalité des boites de commandes) du poste de pilotage
- la totalité des indicateurs)

4. L'APPORT DE LA SIMULATION DANS LA REDUCTION DES COUTS ET DELAIS -

On peut dire que l'intérêt de la simulation apparait dans la constatation évidente que toute

erreur de conception ou de réalisation coûte toujours trop cher, d'une part, et que d'autre part le prix à payer est d'autant plus élevé que l'erreur apparait plus tardivement dans le déroulement du programme.

A chaque étape du développement, en effet, la correction d'erreurs ou d'anomalies s'accompagne de répercussions nouvelles qui aggravent progressivement les conséquences qui en résultent sur le plan du coût et des délais. Il suffit pour s'en convaincre d'observer le déroulement du programme d'industrialisation des équipements :

- avant que ne débutent les travaux de réalisation, les seules répercussions qu'entraîne une modification de la définition ne se traduisent que par une évolution d'un document, la spécification technique de l'équipement : on peut dire qu'à ce stade là, les conséquences sont mineures.

- à partir du moment où le processus de réalisation est engagé, toute modification a une implication directe en terme de délais sur son déroulement dans la mesure où elle remet en cause tout ou partie du travail déjà réalisé. Parallèlement, sur le plan des coûts, l'application d'une remise à niveau des équipements déjà réalisés est d'autant plus coûteuse que leur nombre est important.

En outre, les moyens industriels (matériels et humains) que l'équipementier doit alors mobiliser pour réaliser ce travail imprévu sont nécessairement distraits du potentiel mis en place : il en résulte inévitablement une inflation des charges de production et donc une raison supplémentaire de glissement des délais.

Il apparait dès lors fondamental de mettre en place des simulations, seules susceptibles d'apporter à tous ces niveaux l'avance de phase nécessaire.

Les avantages en sont d'ordre divers et apparaissent à tous les stades du programme.

1. Le premier avantage résulte de la nécessité qu'il y a à disposer, le plus en amont possible du programme, d'une définition détaillée de l'avion et des systèmes qui lui seront intégrés tout en ayant la certitude que les solutions techniques retenues pour réaliser les fonctions envisagées sont du domaine du faisable.

   C'est le rôle du simulateur d'études prospectives d'abord, puis du simulateur de développement ensuite : à ce stade, le simulateur constitue le point de rencontre des ingénieurs de conception et des pilotes d'essais qui y trouvent l'outil indispensable pour évaluer en profondeur les solutions préparées.

   Il est ainsi possible de mettre sur pied et de valider la solution choisie avant que ne soit lancée la phase d'industrialisation.

   Il s'agit là du premier filtre, celui qui permet d'éliminer l'essentiel des erreurs de conception qui, comme on l'a vu, risqueraient d'avoir un effet néfaste sur la suite du programme.

   Il faut d'ailleurs noter que ceci est particulièrement vrai pour les définitions de matériel des équipements et des systèmes : en ce qui concerne la part du logiciel, les possibilités d'en faire évoluer la définition peuvent être envisagées par la suite et même assez tardivement du moins tant qu'elles ne remettent pas en cause l'architecture d'ensemble.

2. Une fois la phase de réalisation des premiers équipements achevée, il reste à vérifier que le produit sous sa forme avionnable non seulement satisfait aux objectifs qui lui ont été fixés mais aussi qu'il s'intègre harmonieusement à l'ensemble de l'avionique et à l'avion lui-même. Il est de la plus haute importance, à ce niveau du programme, de détecter aussi tôt que possible, toutes les insuffisances qui pourraient apparaître dans ce domaine.

   Le simulateur d'intégration apporte la réponse appropriée à cette exigence par la capacité de représenter l'avion couplé à ses systèmes dans des conditions de réalisme qui apparentent son fonctionnement aux conditions du vol réel. L'avantage du simulateur réside en outre dans des possibilités supplémentaires qui lui sont propres :

   . possibilité de "concentrer" les essais : le simulateur apporte la facilité de circonscrire les conditions d'essai autour du cas de vol ou de la configuration critique.

   . possibilité de reproduire à volonté les circonstances d'une anomalie.

   . facilité d'analyser en temps réel, le fonctionnement des équipements.

   . facilité de modifier, toujours en temps réel, l'état logiciel d'un calculateur (par émulation) pour rechercher, par exemple, la solution d'une insuffisance constatée au niveau des performances opérationnelles.

3. Après le premier vol de l'avion et tout au long de la phase d'essais en vol, le simulateur d'intégration constitue encore un soutien irremplaçable par la possibilité qu'il donne de répéter au préalable les vols d'essais, dans la configuration de systèmes et les cas de vol prévus au programme d'essais, avec même la participation de l'équipage qui prendra les commandes de l'avion.

   Il est ainsi possible d'éliminer du programme les configurations ou les cas de vol pour lesquels le comportement de l'avion pourrait se révéler hasardeux.

Au-delà des assurances que celà apporte sur le plan de la sécurité, celà permet aussi d'éviter des interruptions de vols d'essais consécutives *à des déconnexions trop fréquentes de calculateurs* ou encore à une incompatibilité entre l'état des systèmes et les objectifs d'essais. De tels incidents de vol sont, on le conçoit bien, toujours préjudiciables au programme général des essais en vol tant sur le plan des délais que, compte tenu du prix de l'heure de vol, sur celui des coûts.

4. Dans la phase de certification, enfin, le simulateur possède l'avantage certain de permettre l'analyse des cas de pannes qui, soit présenteraient du point de vue de la sécurité du vol, des risques trop grands, soit seraient impossibles à réaliser au cours de vol réels.

De ce point de vue, le simulateur permet de toute évidence une économie en heures de vol dont l'incidence sur le plan des délais et des coûts est, là aussi, positive.

En conclusion, s'il est en réalité difficile de pouvoir chiffrer les bénéfices que l'AEROSPATIALE a retiré de l'utilisation des simulateurs de vol dans le développement des programmes Airbus, il n'en n'est pas moins certain que leur contribution a été décisive dans l'élimination des aléas qui peuvent mettre en péril leur déroulement.

Pour s'en tenir à l'expérience la plus récente, on peut aujourd'hui constater que des premiers résultats très encourageants ont été enregistrés dans le programme A320 alors même que celui-ci apparaissait au départ comme un pari technique particulièrement audacieux.

Il est hors de doute que de tels résultats n'ont été rendus possibles qu'à travers une préparation et une mise au point initiales minutieuses où la simulation a joué un rôle prépondérant.

PROTOTYPE MANUFACTURING TECHNIQUES FOR REDUCING COST, SCHEDULE, AND TECHNICAL RISK

by

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This paper explores techniques employed by the Boeing Military Airplane Company to efficiently produce prototype flight hardware. A number of fabrication methods presented herein were developed during the company funded Brave 200 and Brave 3000 Autonomous Vehicle Programs. Experience gained during other prototype/short production run activities is also included.

Since CAA and CAD are now standard up front engineering procedures (aerodynamics, surface lofting, stress models), the computerized information can be readily adapted to automated tooling and manufacturing activities. Accurate master models traditionally consume a great deal of tooling flow time and represent a significant cost item. Three examples of low cost master models by computer assisted techniques are: 1) N/C scribed header templates; 2) N/C cut precision data sets; and 3) N/C machined models. By adapting complete surface definition data sets, a 50 percent reduction in master model costs can be realized over traditional model generation methods.

Once models have been generated, several options exist when constructing fabrication tooling. Dependent upon program objectives, a particular level of tooling, from soft to hard, may be selected. Plaster layup tools for composites have been developed as a highly reliable, lowest cost method for single part advanced composites fabrication. Cast epoxy compression molding tools have yielded excellent results for up to 12 parts under standard molding temperatures and pressures. Electroformed nickel has proven to be a cost effective prototype tooling technique which can be transitioned into production.

Next in the prototype process, a number of manufacturing techniques are employed to fabricate metallic and non metallic components. Of particular importance is the correlation of prototype manufacturing processes to expected future production methods. This is due to the fact that, the customer is now recognizing that product cost is equally as important as product performance. Production manufacturing processes are utilized whenever possible, and are, in certain cases, more cost effective than one of a kind, prototype techniques. This is a value added philosophy that can save significant time and money in the latter development and production program phases.

1.0 SUMMARY

The approach and ideology necessary to develop a plausible prototype hardware manufacturing concept requires diligent efforts by all involved personnel. This text has addressed the philosophy employed by a leader in the aerospace industry, Boeing Military Airplane Company. The following is a review of the key elements of this philosophy.

1.1 COSTS/SCHEDULES

Careful cost and schedule planning are necessary during the preliminary efforts of the developmental program. If a prototype concept is not economically feasible or requires excessive manufacturing time, the possibility of producing acceptable prototype hardware is slight. Also, any impacts to the production efforts that financially sustain a corporation must be assessed.

1.2 DISCIPLINE RECIPROCATION

Direct interaction between design and manufacturing must occur from the onset of the program. Components, subassemblies, and full assemblies must not only be design functional, but also manufacturable. Cooperation between all disciplines perpetuates the ability to readily and cost effectively manufacture prototype hardware.

1.3 INNOVATION

Finally, innovative techniques as well as proven methods must be applied to the program. The manufacture of prototype hardware supplies the perfect proving ground for technically advanced methods that, if successful, will have infinite value in the production arena. The proper balance of these fabrication techniques can be achieved through logical thought and planning.

2.0 INTRODUCTION

Prototype development programs are crucial for economic survival. If properly managed, these programs generate new business opportunities, stimulate competition, and spawn technical advancement. Poorly directed activities are not only time consuming, they are the harbinger of financial devastation.

Boeing Military Airplane Company (BMAC) has had extensive experience with developmental programs based on the manufacture of prototype hardware. Through efforts that blend standard manufacturing procedures with state-of-the-art concepts, a solid foundation of proven manufacturing techniques has evolved. Examples of recent BMAC programs involving construction of prototype hardware include the Brave 200 and 3000 systems and various other programs. (See Photographs #1 and 2)

Photograph #1 Brave 200

Photograph #2 Brave 3000

2.1 PROTOTYPE DEVELOPMENT VIABILITY

The goals and objectives to be obtained through the program are foremost. To ensure success of a program and reach these goals, several factors must be taken into consideration: fiscal planning, time management/scheduling requirements, and design/manufacturing interaction. The information flow between these elements is illustrated in Figure #1.

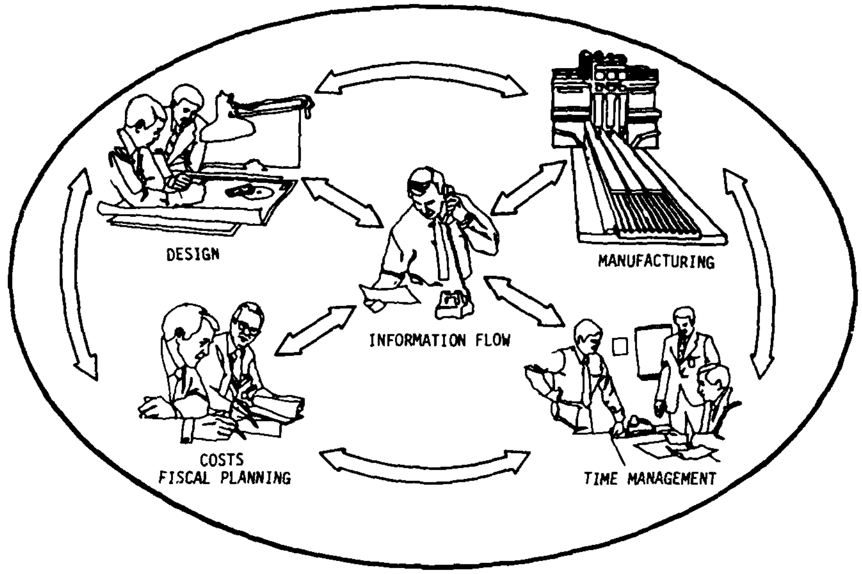


Figure #1 Information Flow

2.1.1 ECONOMIC FEASIBILITY

The economic feasibility of such a program must be carefully determined. Cost estimates must be generated from initial concepts and preliminary technical assessments. These estimates should be based on previously gathered (historical) manufacturing data. While no program can be guaranteed a success, careful financial planning and analysis will reduce the economic risks to a minimum. Also, since a large amount of expenditures for capitcl equipment would prove cost prohibitive, the utilization of in-house equipment/capabilities is a necessity.

2.1.2 SCHEDULING

The impact of prototype production to current activities must also be determined so as to reduce bottlenecks and conflicts. Although the optimum solution is to isolate the prototype from mainstream production, this is not always possible. A delicate balance between a quick-paced schedule and a realistic schedule is required.

2.2 DISCIPLINE INTERACTION

Successful completion of a development program consisting of the construction of prototype hardware also requires interaction between design and manufacturing. Such cooperation is important during program conceptualization and full scale program planning. As the concept is being created, a process formulation between design and manufacturing must take place. Both the design and manufacturing disciplines need to be cognizant of each other's activities. Design cannot dictate components that are impossible to fabricate and manufacturing cannot be oblivious to structural/functional requirements.

From these reciprocal activities, a manufacturing scenario evolves. The plan is composed of both proven and innovative methods that will result in the successful fabrication of prototype hardware. While the plan is unique and prototype oriented, production adaptability will further promote the program's benefits. Also, the fabrication and tooling methods that constitute the manufacturing plan must be tailored to the component design, stay within the available resources, and demonstrate as closely as possible planned production methods.

3.0 SYSTEM DETAILS

The evolution of prototype hardware from a design concept to functional, physically existing components, can be considered a unique development system. The generic elements of the system (from design, through manufacturing, and final assembly) are not, however, categorically unique. The factors that create an unparalleled prototyping system are the manner of methods utilization, approach tailoring, and the ingenuity of those individuals involved. Figure #2 illustrates the logical path of a simplified prototype development system. For example, to achieve Objective #2, the correct path could be Design Option #1, complemented by Fabrication Method #4 and Tooling Method #2.

	OPTIONS AVAILABLE			
REQUIRED OBJECTIVES	1	2	3	4
APPLICABLE DESIGN	1	2	3	4
APPLICABLE FABRICATION METHOD	1	2	3	4
APPLICABLE TOOLING METHOD	1	2	3	4

△ LOGICAL PATH

Figure #2 Prototyping Systems Options

3.1 DESIGN

The initial step in the development of prototype hardware is the creation of the design concept drawing (or series of drawings). This phase should include all standard practices and procedures necessary for proper component/system design. As previously indicated, manufacturing viability should also be a design concern.

The design process is accomplished either manually or through the use of computers. Computer-Aided Design (CAD) and Computer-Aided Engineering (CAE), if available, are a definite aid in the design of prototype hardware. Design quality, engineering productivity, and technical decision methodologies are greatly enhanced. Revisions can be made in a matter of seconds and all pertinent data may be reviewed, manipulated, and stored, thus making the digitized information more valuable than the engineering drawing. BMAC has experienced an increase in design efficiency of roughly 30 percent through the application of these advanced disciplines.

3.2 NUMERICAL CONTROL AND COMPUTER AIDED DESIGN (CAD)/COMPUTER AIDED MANUFACTURING (CAM)

Creation of a Numerical Control (N/C) data set (or series of data sets) directly follows the design phase. The required N/C information can be taken from design drawings or compiled directly from the CAD system (i.e., CAD/CAM). N/C data sets can be easily and quickly manipulated or changed, if so required. The N/C information can relate to either components and tools and can be utilized in the construction of both. Furthermore, the N/C data becomes a permanent record of the prototype design that can be used for reference or

full scale production. Comparatively, BMAC has achieved cost savings of 25 percent and labor savings in excess of 20 percent through the application of N/C technology.

3.3 MODEL GENERATION

Prior to actual prototype hardware manufacturing, it may be valuable to construct a scaled model of the concept, as shown in Photograph #4. The model will be valuable as a visual aid and also as a guide for fit and function. The scaled model is usually hand constructed from inexpensive materials.

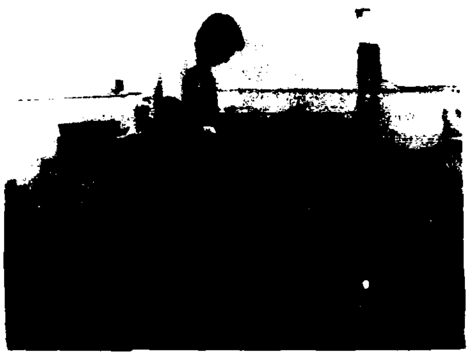
Photograph #4 1/2 Scale Model - Brave 3000

3.4 FABRICATION CONCEPTS

Concurrently with the prototype design phase, possible component fabrication methods are determined. Fabrication of prototype hardware can be accomplished through either hand-oriented or equipment-oriented operations.

3.4.1 MANUAL PROCESSES

Hand operations, as in Photograph #5, are best suited for small production lots or when sophisticated equipment is not available. Extremely complex components also readily lend themselves to these processes. Highly skilled individuals are required to ensure component integrity and reduce excessive lead times.



Photograph #5 Hand Layup Operation

3.4.2 MECHANIZED PROCESSES

Equipment/machine-oriented prototype fabrication methods offer extreme accuracy and exact reproducibility. Prototype fabrication using equipment also supports exceptional schedule flexibility, future production cost visibility, and large production lots. However, because a large amount of capital is required for equipment purchases, mechanized fabrication is generally restricted to in-house resources for prototype manufacturing. In general, BMAC maintains that initial equipment expenditures should be less than 20 percent of the program's overall budget.

3.4.3 METHODS EVALUATION

Determination of the most applicable fabrication methods, whether hand or equipment oriented, is made by assessing component type/size, material type, available resources, and the number of units to be produced. (See Figure #3.) The program budget dictates total expenditures, hence fabrication approaches must be tailored to fit within this constraint. Also, schedule requirements must be considered so as not to adversely impact the program. Generally, a combination of both hand and equipment operations is appropriate. This combination approach is applied to individual components as well as entire assemblies.

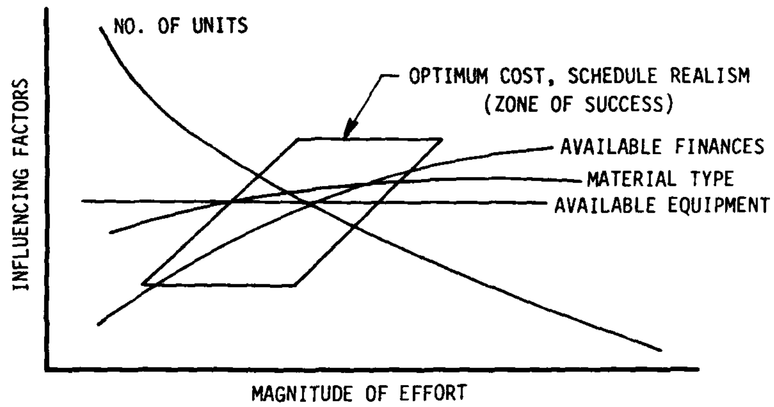


Figure #3 Methods Evaluation

3.5 TOOLING CONCEPTS

Tooling concepts/types are directly influenced by the fabrication method and by the design and load requirements of the prototype hardware. Within the scope of the program, tool types can vary greatly in form, material type, and construction. Creation of an accurate master model is critical to tooling accuracy for non-direct N/C fabricated tools. (See Figure #4.) Generally, this master is of a soft (plaster) construction, as in Photograph #6 For prototype hardware manufacturing, BMAC employs N/C data sets, ensuring accurate master models. N/C is additionally useful because it can be used to determine tool accuracy through tooling proof boards and it accommodates quick data changes.

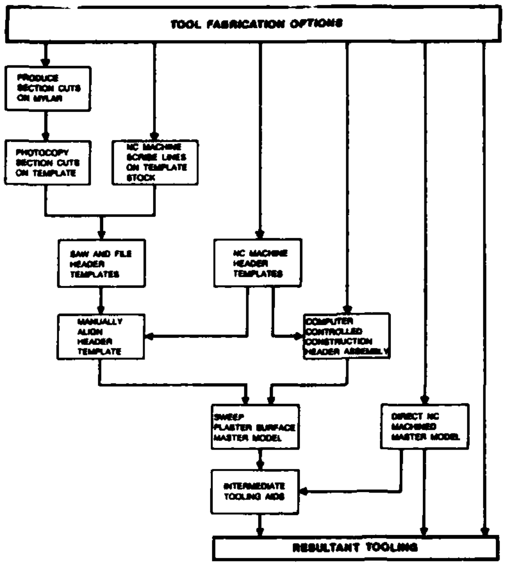


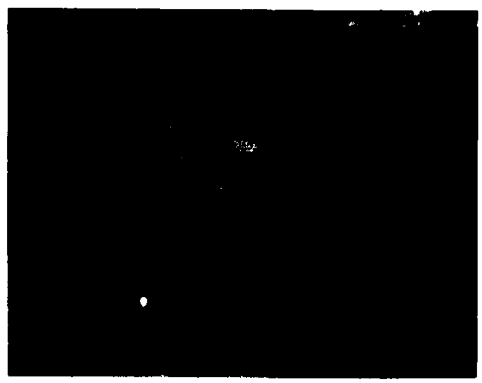
Figure #4 Tool Fabrication

Photograph #6
Typical Master Model

3.5.1 SOFT TOOLS/MASTER MODELS

The initial step in producing the master model is the construction of station templates or headers. These headers define the size, shape, and contour of the model. N/C data is utilized to machine the headers to precise dimensions. The machined templates are then aligned as in Photograph #7 and a plaster tooling medium is troweled across to complete the desired contour. Photograph #8 depicts the troweling operation which is man-intensive and requires skilled personnel. BMAC has created both N/C assisted and complete master models through N/C machining, realizing a 30 percent man hour saving over hand operations. The versatility of the model as well as the low cost of the tooling material allows this process to be economically favorable. Once completed, the master model becomes the cornerstone of nearly all tooling for prototype hardware manufacturing.

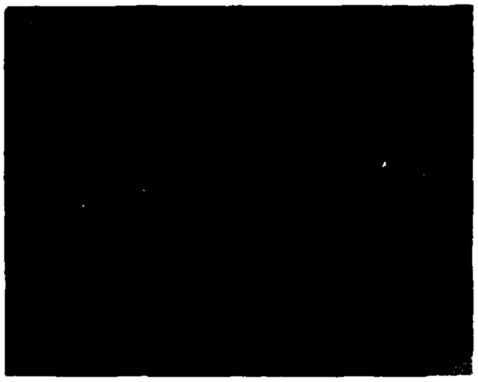
Photograph #7
Alignment of Surface Definition Templates



Photograph #8
Master Model Construction

3.5.1.1 LAYUP MANDREL

A cast (or splash) of the master model can be taken to create a layup mandrel (LM). (See Photograph #9.) The LM can be of plaster or a castable composite material, depending upon the life cycle requirements. Generally, plaster LMs are one-time, "sacrificial" tools while epoxy-based LMs offer more durability. Either a male or female LM may be made from the model, depending upon the number of casting operations and the component configuration. The casting is done by hand, but produces accurate tooling at relatively low costs.



Photograph #9
Plaster Cast with Master Model

3.5.1.2 ELECTROFORMED TOOLS

Layup mandrels are not the only applications for casting from a master model. A cast may also be used in the electroforming of nickel tools. This process involves immersing a casting (or a combination of castings) in a tank containing a nickel based solution. The solution is charged electrically and nickel particulates begin to precipitate upon the cast. The final step is to break the casting away from the nickel tool and attach the required support frame. Photograph #10 is an example of the electroformed tools used by BMAC.

Photograph #10
Electroformed Nickel Tool

3.5.2 MACHINED/HARD TOOLS

It sometimes becomes necessary to use hard (aluminum, steel, etc.) tools for the production of prototype hardware. Rigorous processing parameters and complex component designs mandate the need for these tools, such as in most compression molding operations. Costs and impacts to production schedules can be reduced by using N/C data sets. The numerical

information can be generated from design drawings, or, if CAD is available, can be transferred directly to an N/C milling machine. To reduce excessive material loss and machine down time, an N/C proof board or preliminary tool model is machined to determine any flaws in the data set program. (See Photograph #11.) After the data set has been evaluated for accuracy, the actual machining process takes place. Provided this technique is properly and logically applied, these tools can be economically used for prototype hardware. N/C machined tooling costs are offset by extreme product accuracy, extended tool life, and a smooth transition into full production. Complete CAD/CAM, N/C produced tools have overcome the stigma that equates machining with high cost.

Photograph #11 N/C Proof Board

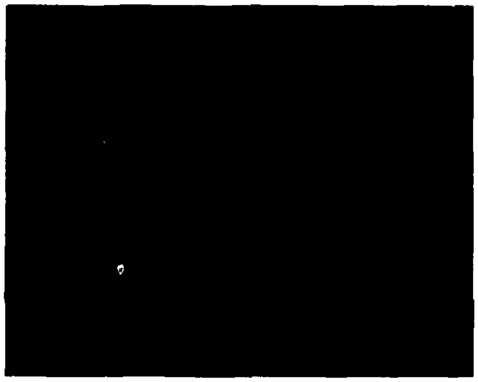
3.6 MANUFACTURING DETAILS

Following is a brief description of various fabrication methods employed by BMAC for the production of prototype hardware. While these methods in themselves are not unique, the order of their utilization, the approach tailoring, and the logic applied by BMAC is revolutionary to the manufacture of prototype hardware.

3.6.1 HAND LAYUP

Hand layup is by far the most labor intensive fabrication method used for the manufacture of prototype hardware. It is, however, best suited for some applications. Small production lots and extremely complex shapes that are to be heavily loaded generally lend themselves to hand layup. Photographs #12 and #13 depict hand operations for both large and small applications. Cure and consolidation will take place using layup mandrels and an oven/vacuum or autoclave environment.

Photograph #12
Hand Layup Construction



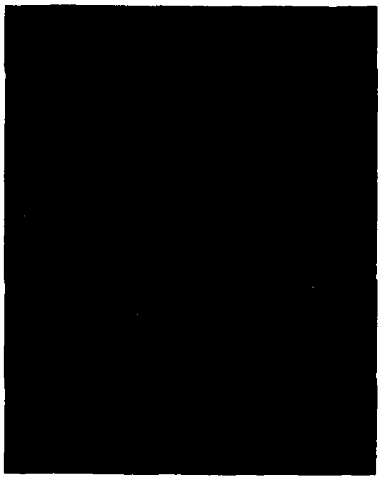
Photograph #13
Brave 200 Layup Mandrel

3.6.2 RTM

Resin Transfer Molding (RTM) provides a medium production rate fabrication method or may be used as a prototype for compression molding. Equipment and tooling costs for the process are relatively inexpensive and production time is expedited 30 percent when compared to hand layup. The tools are generated from a plaster cast of the soft master model. This cast, along with the required interior substructure, becomes the female cavity of the mold. The male plug is also constructed from this cast. The final RTM mold is generally composed of epoxy with a metallic filler for strength. The actual molding process involves placing a chopped mat reinforcing material into the mold cavity as required by the component design. Photographs #14 and #15 depict the filler in the cavity as well as the tool's orientation in the multi-position clamp. The resin is then pumped into the closed mold until an adequate amount has been infused. It should be noted that only resin flow, not fiber/filler slip, occurs under the low pressure of the molding operation. The finished product, shown in Photograph #16, displays the lack of waste material and flash associated with this process, thus reducing clean up and assembly time by roughly 10 percent.

Photograph #14
Locating Reinforcement in an RTM Mold

Photograph #15
RTM Mold Closure



Photograph #16
Completed RTM Component

3.6.3 RIM

Reaction-injection molding (RIM) is utilized as the process for forming structural components such as the air foil shown in Photograph #17. The RIM system in Photograph #18 is capable of not only prototype, but also full production operations. For the construction of prototype components, composite (Ep/Al) tools are utilized because of their relative low cost. RIM produced hardware possesses a superior surface finish, and since mold residence time is short, this process allows for a direct transition from prototype to production. As in RTM, the reinforcement is placed (where required) in the mold cavity, the mold is closed, and the resin is injected. To expand our technical data base and to further optimize the RIM process, BMAC has performed extensive testing of RIM-produced aerodynamic structures. A portion of this testing led to mold orientation standards based on the shape and contour of the component.

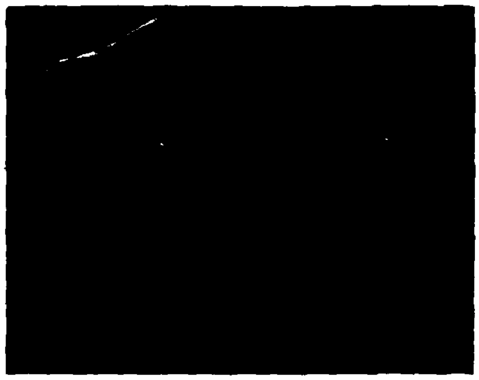
Photograph #17
Brave 200 Foam Reinforced Wing

Photograph #18
BMAC RIM System

3.6.4 COMPRESSION MOLDING

Compression molding is being utilized for small, complex contour details (Photograph #19) as well as large structural components (Photograph #20). Tools for the process begin with the soft master model and evolve into dies capable of adequate prototype hardware production. Depending upon the shape of the components and the number of units to be produced, compression mold dies may be constructed of composite materials with steel or aluminum base surfaces. The die in Photograph #21 is of this construction and contains integral heating/cooling lines. For deep, sharp drops or large production lots, solid steel dies are a necessity. (See Photograph #22.) Construction of these dies is expedited through the utilization of the CAD/CAM principles previously discussed. While these dies do increase the cost of prototype hardware (by approximately 25 percent), careful planning will facilitate their use in a production environment, thus actually reducing total expenditures and valuable time.

Photograph #19
Brave 3000 Compression Molded Tail Cone Assembly



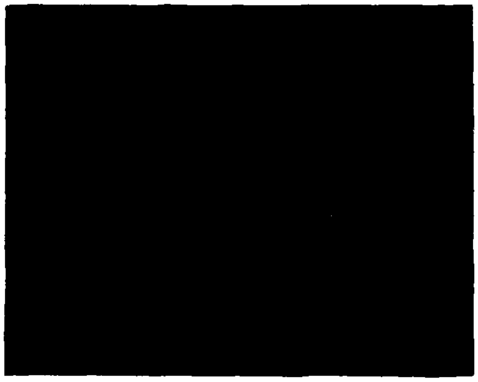
Photograph #20
Brave 200 Compression Molded Body Sections (Details added)

Photograph #21
Epoxy/AP Compression Mold Tool

Photograph #22
Tail Cone Ring Steel Compression Mold Die

3.6.5 PULTRUSION

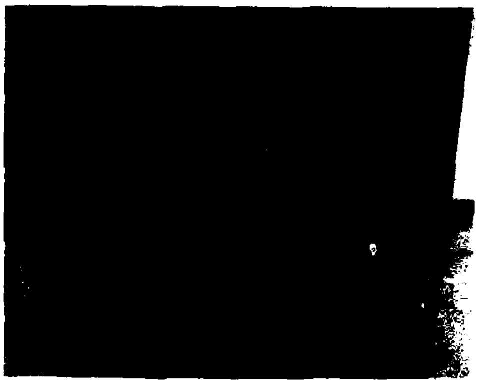
Pultrusion is an innovate process to the aerospace industry and, although the associated die and equipment for the fabrication of prototype hardware is somewhat costly, the method is directly transferable to a production mode. The prototype fuselage section shown in Photograph #23 reveals the accuracy of the process. Production rates are extremely high for pultrusion and through an ingenious design, have been made even higher. The fuselage and related body sections of the Brave were designed to be interchangeable due to the location of their assembly joints. Hence, one tool produces three individual components that differ only in length, creating a dramatic comparative tooling savings of 70 percent. Also, the nature of the pultrusion process reduces component clean up and assembly preparation procedures.



Photograph #23
Brave 3000 Pultruded Body Sections

3.6.6 FIXTURING AND ASSEMBLY

In most instances, fixturing and assembly of prototype hardware is done by hand. The nature of the components lend themselves to this man intensive operation, with assembly being done via adhesives or mechanical fasteners. If extremely precise jigs or locating devices are required, N/C can be utilized as the most effective means of achieving the desired results. The N/C data sets necessary to produce the fixtures can be taken directly from those previously generated for tool construction, thus reducing costs. Also, BMAC has made the assembly of prototype hardware more cost effective by utilizing component construction tools as assembly fixtures, thus completely eliminating the expenditures for assembly tooling in some instances. For example, the air foil layup mandrel in Photograph #24 is also used as an assembly jig. Generally, one can expect more mechanical fasteners on prototype hardware due to increased assembly/disassembly, modifications, and field repairs.



Photograph #24
Combination Layup Mandrel/Assembly Jig

4.0 CONCLUSION

Programs involving the manufacture of prototype hardware offer rewards to those companies willing to accept the challenge. Boeing Military Airplane Company has excelled at meeting these challenges with a proven record of successful development programs. In addition, future programs will utilize neoteric technologies and disciplines such as Computer-Integrated Manufacturing (CIM) to direct and integrate all required fabrication and assembly processes. Logic, innovation blended with tradition, and careful planning are the keys to BMAC's success.

STRUCTURAL MATERIALS - THE CHANGING SCENE

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SUMMARY

Structural materials for use on aircraft have, in the main, evolved by minor development from a previously existing base. These developments, which have been by small increments, have been fairly leisurely in the timescales involved.

The major exception to this in the last two decades has been the introduction of fibrous composites which, whilst achieving a revolutionary change, has been effected against protracted timescale.

Developments are currently underway, or are being anticipated, which will require other revolutionary materials to be introduced but to much tighter timescales and against aircraft project requirements.

The paper identifies examples where this development should be directed and proposes action necessary to ensure that the materials are developed to a common requirement in the required timescale.

INTRODUCTION

Since the 1950's the structural backbone of the aircraft industry has relied almost entirely on aluminium alloy., with small applications of other metals, both ferrous and non-ferrous. By the 1960's their dominant position was being challenged by high performance composite materials primarily those reinforced by either Boron or Carbon fibres. Their use offered the opportunity of reducing structural mass, allowed the aeroelastic tailoring of structures and the production of shapes difficult. if not impossible, in conventional materials.

Twenty years has elapsed and only now can composites claim their rightful places as a major element of aircraft structures; and primarily in the military field. New and exciting projects face us for which it will be necessary to develop existing materials to meet the requirement or create new ones to satisfy a specific need. Can we afford to wait the two decades mentioned above for these essential developments to mature? The answer is surely; No!

CURRENT STRUCTURAL MATERIAL STATUS

The majority of military aircraft are exposed to manoeuvre envelopes in which the kinetic heating is sufficiently low that it allows the use of conventional aluminium alloys, or the current generation of thermosetting epoxy composite systems. Where this is precluded, and these areas are in general limited, titanium and steel alloys are used.

The development of aluminium alloys has been one of gentle, small steps towards a general goal of improved specific strength, toughness and fatigue performance. A family of materials have therefore been developed that optimise the material properties for specific applications allowing the designer a reasonable degree of flexibility in his choice.

The introduction of the high strength Aluminium-Lithium alloys will yield a specific advantage over the existing 7000 series alloys of some 10% but this lloy is not yet with us and may not be available until the turn of the decade; if not the century! If the material is capable of being developed why should, and does, it take at least a decade for these fruits to be harvested?

In the field of composites, the first generation of materials have found their application and current aircraft are employing in the order of 40% of the material in their structures. From the beginning, circa 1970, these materials were known to possess advantages over the aluminium alloys, but with their introduction came a number of disadvantages. From the structural standpoint the largest of these disadvantages were their poor resistance to low energy impact and the degradation of compressive strength when tested under hot/wet conditions. These deficiencies have been known for more than a decade and only now are materials becoming available where greater advantage is being taken of the inherent fibre properties. Again why has it taken so long to obtain a 20% improvement in material properties?

The above two examples have shown that material developments inevitably will take place but that the timescales currently involved are lengthy. There appear to be no obstacles to the reduction of timescales that cannot be overcome and how this can be achieved must be addressed. However, before this, let us consider areas into which effort should be applied to produce materials to satisfy some of our medium and long term goals.

MATERIALS REQUIRING DEVELOPMENT

As with other major airframe manufacturers, British Aerospace are actively involved in the design of military aircraft in which the environment to which they are exposed allows the use of currently available metallic and composite materials. Any developments must clearly be directed at achieving significant improvements in these materials, of the order of 10-20%, and must be focused on specific objectives. Let us consider the materials and developments required.

For aluminium the promise of the Lithium alloy must be realised and taken further either by developments of this family of material or by the use of this material in the production of metal matrix composites. The latter offers the potential of achieving the 20% improvement and is possibly the area in which investment will reap the largest rewards.

A process development, elusive to date, that would revolutionise the structural design of aircraft would be the ability to diffusion bond aluminium alloys. During this process the oxide film which rapidly forms on the surface is required to diffuse into the parent material, when subjected to temperature and pressure, and allow an homogenous material to be produced at the interface. Whilst this diffusion process takes place with titanium alloys, success has not yet been achieved with aluminium. The known ability of Aluminium/Lithium alloys to undergo superplastic forming has focused attention on the resolution of this problem. With the successful development of this process, structures could be produced in which the standard fasteners, rivets and bolts, would be virtually eliminated: the consequent effects on mass and fabrication costs are obvious.

The development of fibrous composites appears to be one area with a high possibility of success. The first generation of materials are now being replaced by the toughened epoxies incorporating improved fibres, yielding improvements in specific properties of at least 20%. Even with these the properties achieved on structurally representative elements are only a small proportion of those theoretically achievable from the fibre. Co-ordinated effort must be directed at understanding in greater detail the mechanisms of failure in all structural modes, notched tension, notched compression etc., in order that the material can be optimised. Greater attention must, in particular, be paid to the interface between the fibre and matrix as this plays an important role in many of the significant failure modes.

Whilst epoxy based composites from the foundation of current applications, up to 120°C operating temperature, other matrix materials, for example polyiamides, bismaliamides and thermoplastics, offer improved properties at elevated temperature. This benefit can also be used at the lower temperatures as the drop in properties under hot/wet conditions is less pronounced. However, other difficulties preclude their general use at these lower temperatures. With thermoplastics, for example, the structural benefit is offset by the increased material costs and the processing difficulties associated with their use. This is the area where development effort must be directed if these materials are to find large scale application on conventional aircraft.

Titanium alloy development has been spearheaded through the engine manufacturers, for obvious reasons, and the application to aircraft structures has been very much a spin-off from this research. The reinforcement of Titanium by either particulate or continuous fibres, such as silicon-carbide, and their subsequent introduction into structures fabricated using SPF/DB technologies would allow structures to be produced competing favourably with those using aluminium alloys.

As the temperature of the structures increases the materials available to the designer decreases and above approximately 850°C, his choice is extremely limited. Even above, say, 250°C the choice rapidly declines and the use of titanium alloys becomes more prevalent. With advanced take off and vertical landing aircraft, the transient engine efflux effects produce temperatures and acoustic environments, particularly on the lower surface of the aircraft, requiring the development of the above mentioned materials to these applications.

The biggest challenge to the materials and manufacturing process engineer is that offered by space. Current payload launch systems are either non reusable rocket systems, such as Ariane, or those capable of multiple missions, namely the U.S. Shuttle vehicles. The latter is exposed to re-entry temperatures in excess of 1500°C and, as a consequence, is thermally protected to prevent the structural integrity being compromised. This potentially makes for a non-optimum structure and a vehicle requiring a prohibitive amount of effort on turn round. The goal must therefore be to develop materials which have structural efficiency at these high temperatures such that the total structural mass is lower than that produced by the use of insulation. Carbon fibre reinforced carbon (C-C) has been used in areas of extreme temperature, missile noses and rocket efflux cones, but the specific strength of these materials and their lack of resistance to an oxidising environment precludes their direct application to re-usable space vehicles. A material with specific properties equal to or greater than conventional aluminium alloy is required capable of operating repeatedly at 1500°C. Can carbon-carbon be developed to this level or are there other materials in the ceramic composites family that will more readily meet the goal? At the opposite end of the temperature spectrum, the environment existing in the cryogenic fuel tanks requires materials capable of performing efficiently from 20°K upwards are required. The greater the temperature range the less insulation is required to ensure these structural tanks perform satisfactorily during the re-entry and landing phase of the mission. Current contenders are titanium, and in the non-metallic field carbon reinforced thermoplastic materials such as PEEK. The development of high temperature versions of this material are ongoing and certain versions are available on a production basis.

The above is a short, and incomplete, description of the areas in which structural materials require development. Figure 1 shows on a quantified scale the specific strength of various materials and the direction in which development should go to maximise the efficiency of vehicle structures. The abscissa is the temperature to which the structure will be exposed along with an indication of the temperature ranges over which three types of vehicle will operate. These are representative of a modern conventional fighter, an advanced short take-off and vertical landing aircraft and a re-usable space launcher.

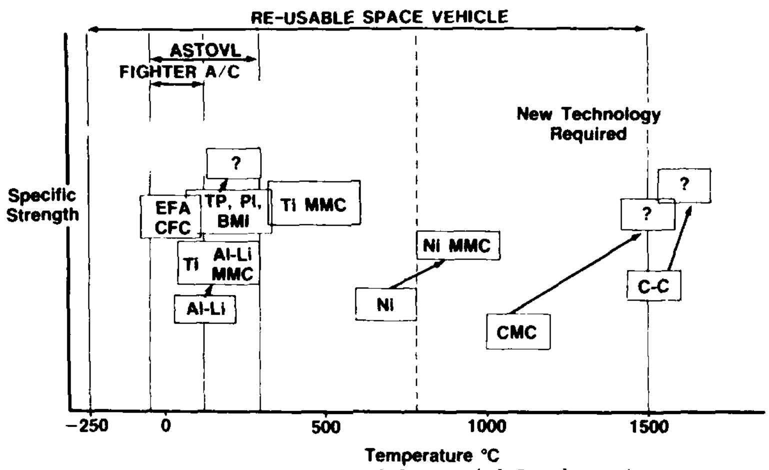

Fig. 1 - Potential Material Developments

Figure 2, again using these three projects as the abscissa attempts to depict that developments of existing materials will satisfy the requirements of the first two projects but that for the latter, new material manufacturing technologies will have to be developed.

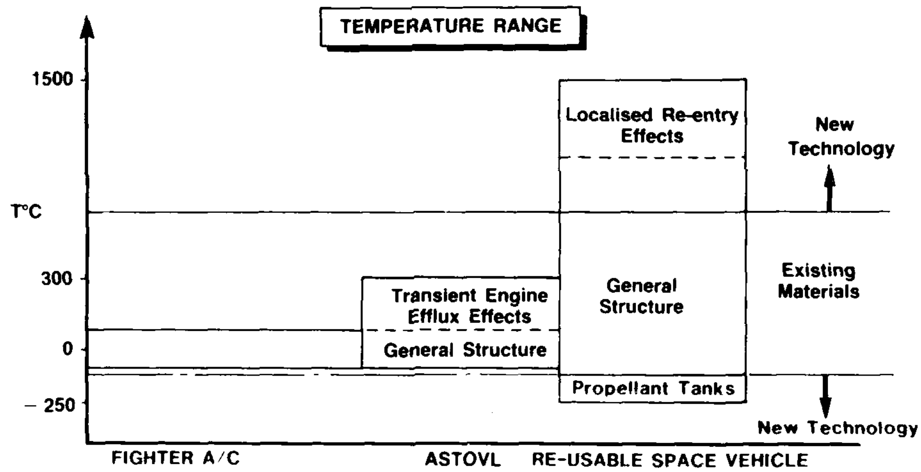

Fig. 2 - Material Requirements

CURRENT MATERIAL DEVELOPMENT TIMESCALES

It is difficult to identify when a material development is either started or reaches completion, but it is reasonable to say that from observing a potential application to the material maturing to this application requires something of the order of ten to fifteen years. Figure 3 has been produced to show these timescales for currently available materials and indicates that whilst some development is proceeding on the more exotic materials, the availability of these in timescale terms is ill defined. Can the aircraft industry afford to wait the traditional development period of ten to fifteen years for these materials to reach fruition? Consideration has been given to the historical development of carbon-carbon composite materials within the United States and the increase in structural performance against time is plotted on Figure 4. Up to 1970 the materials available had very poor strength and their development up to this date had been leisurely. With the injection of funding for the Shuttle programme the rate of improvement increased and has provided the materials available to date. In order to meet the improved performance requirements of re-usable space vehicles consistent with the timescales for the provision of an alternative launch vehicle then a doubling of certain of the materials specific properties will be required. If traditional development timescales appertain then the required materials will be available by the turn of the century. (One could argue that this is optimistic as the closer the material is developed to its maximum, the more difficult becomes the development). The timescales for an alternative re-usable space vehicle do not allow the luxury of this period and effort has to be directed at reducing it. How is this to be effected?

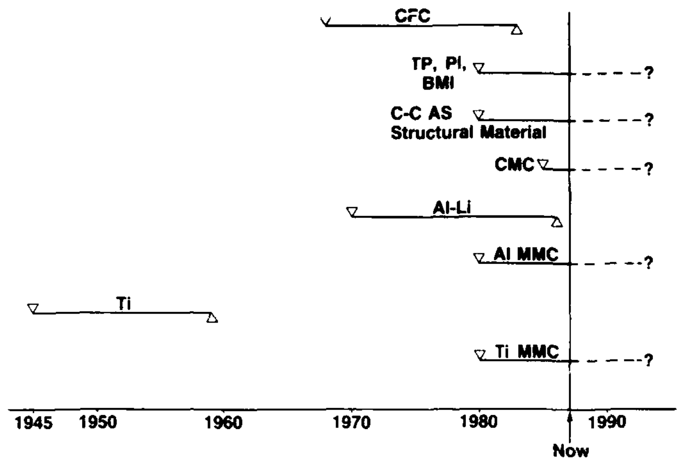

Fig 3 - Material Development Timescales

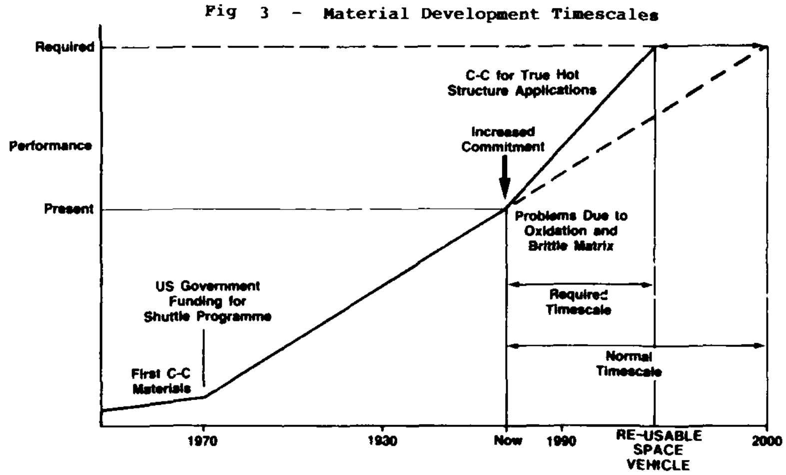

Fig. 4 - Development of Carbon Reinforced Carbon Materials in USA

REDUCTION OF MATERIAL DEVELOPMENT TIMESCALES

The decision to develop a given material or to create a new concept is dependent on a large number of considerations. Of these the two most important are the performance improvements possible and the commercial advantage to the supplier of achieving these improvements. Having decided to proceed with the development, what defines the timescale to achievement and what, if any, are the material suppliers commitment to success? It would appear that the greatest commitment will be generated by maximising the potential application on a worldwide scale and it would therefore appear prudent to commit the maximum number of organisation to defining common development objectives.

The definition of a development requirement is currently somewhat chaotic and is a function of the information collected by the potential supplier from a number of sources. One source would be to solicit the airframe manufacturers for their future requirements. This will yield information, but not necessarily useful, depending on the way in which it is given. The worst scenario would be that of the enquiry being directed at a number of departments within a division of a multi-divisional organisation. Each department will define a different requirement, the fulfilment of which may be at conflict with requirements considered by others to be equally important. For example the structural engineer will require the maximisation of structural performance, the production engineer the minimisation of manufacturing costs, the material procurer the minimisation of raw material costs and the process engineer a material tolerant to a wide range of processing variables. Inevitably the achievement of all these requirements is impossible and compromise is necessary; but sometimes difficult to achieve. This should be readily resolved by the division defining internally its requirements/priorities and presenting the potential supplier with a divisional requirement that, if satisfied, would meet the long term needs of the organisation. Divisions within a corporation may have different views of avenues and the goals of material development but these again are readily solved by the mechanism adopted at divisional level. There now exists a corporate plan for tomorrows materials.

Unfortunately there will be more than one corporate plan due to the existence of, say, twenty major airframe manufacturers throughout the world and, as a consequence, development generally follows the direction indicated by the most powerful, usually of U.S. origin, for obvious commercial reasons. A way has to be defined of allowing commonality of objectives to be defined covering as wide a range of users as possible. A difficult task when standardisation of composite material test specimens has not been achieved within Europe. Despite this obvious difficulty, let us presume that the material supplier has a clear set of objectives that will satisfy multiple clients, and that he believes he is capable of fulfilling the need. The additional ingredients required to enable the work to commence are :-

1) Visibility of long term commercial reward
2) Timescales for development
3) Development funding
4) Human resources

The former being the ultimate driver. Let us consider three of these ingredients in turn and debate how improvements can be effected to reduce the development phase.

1) Timescales for Development

In defining the goals, consideration will have already been given to the timescales appropriate and, in general, they will, with the exception of speculative research, be project driven. This gives a clear set of time related objectives that the supplier can programme himself against. Unfortunately, whilst best intentions are applied to effect the development against a set of timescales, they are invariably not met. This failure can have catastrophic effects on a project relying on such developments. Engines, Avionics etc., require quantum leaps in development for application to new projects and their development is invariably successful. If the same degree of success is to be effected in structural material development then perhaps a lesson can be learnt from the way in which such equipment is procured. The answer appears to be simple: the suppliers of equipment are contracted, with all the power of law to provide the goods to a deadline. Failure to do so makes them liable for compensation. With the clear set of objectives as defined in a previous paragraph then this approach could lead to the development of materials in a more timely manner.

2) Development Funding

It is estimated that the total funding required to develop a family of structural ceramic materials will be in order of $300M. In order to develop the proportion of this, relevant to a re-usable space vehicles, a figure of $120M is predicted as being necessary up to the mid 1990's. The predicted utilisation of material is such that normal development funding available to the supplier either from his own R & D budget or from traditional European funding sources is inadequate to ensure that effort will be directed with sufficient enthusiasm to the production of suitable materials. This can only be effected, where the supplier cannot foresee either a medium or long term market for his product by the pooling of corporate, national and international funding.

3) Human Resources

The pressure to develop these more exotic materials for application to airframe structures requires the introduction of skills within the industry only present currently on a small scale.

Material developments prior to structural composites were, as stated earlier, small steps from proven bases. As a consequence, the methods used to manipulate these materials were improved in parallel with the material improvements but were not in need of radical reform. The manipulation and machining of Aluminium Alloy is a perfect example of this.

With the advent of composites the realisation came that the material suppliers, airframe designers and producers were interdependent. The material had to be developed in parallel with the manufacturing development in such a way that the finished product met or exceeded the designers requirements. It is absolutely essential that the material supplier fully understands the users requirements, not merely having the ability to read and comprehend the specification.

Engineers and scientists are required in both the suppliers and users facilities who have a grasp of the whole picture and can steer the developments to yield the optimum product. With the advent of these new materials, the synergistic union of the engineers in the two camps will assist in achieving the completion of the development activities.

SUMMARY AND CONCLUSIONS

The development of structural materials has, with the passage of time, become a more complex business, with the need for the user and supplier to integrate their thoughts and activities to a common goal. Developments in both metallic and non-metallic materials are essential in timescales previously not achieved if the requirements of future military and space projects are to be honoured. The traditional timescale hitherto have been of the order of ten to fifteen years and this has to be halved to ensure that materials are developed within the period of gestation of a typical project.

The means by which these reductions can be effected have been discussed and the major items considered in need of addressing are :-

1) The identification of material development objectives preferably on an international scale. Failing this it must be achieved either at national or corporate level.

2) The creation of contractual relationships between supplier and user to ensure that the material is developed to meet the timescale requirements of the user. These are not dissimilar to the constraints currently applied to equipment suppliers.

3) The provision of adequate development funds to ensure the more exotic materials, for which a long term application is not visible, are available to meet project needs. This may require the pooling of corporate and government monies to achieve the common goal identified at 1).

4) The education and training of scientists and engineer to meet the challenge where the interaction of material supply and configuration are directly interacted with the subsequent design and component manufacture. These personnel will require an understanding of the total requirement and an ability to judge the effect of compromise on the materials usefulness.

TIME AND COST REDUCTION THROUGH COMPUTER INTEGRATED MANUFACTURE

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SUMMARY

The paper sets out to review the reasons why CAD/CAM, since it's introduction about 10 years ago, has provided only a limited increase in productivity and has had very little effect on the timespan from initiation of design to delivery of the first unit from production.

Further productivity benefits and a reduction in the time taken to produce the first prototype can only be achieved by a more flexible approach to design and manufacture. This in turn puts a greater strain on the Company's support system and a much greater integration of the whole activities of the Company are required. Computer systems are a necessary means of producing the level of integration through Information Technology. This requirement is moving us from CAD/CAM to Computer Integrated Manufacture (CIM).

The paper concludes by a review of the steps being taken within British Aerospace towards reducing project lead times and costs.

1. CAD/CAM - THE PAST

A recent survey (ref. 1) carried out by the British Institute of Management (BIM) and Cranfield School of Management showed that almost 50% of companies surveyed reported that "the perceived payoffs to date from new technology seem to have been low or even non-existent". About 50% of companies that had CAD/CAM systems reported "no significant gain from their introduction". Flexible Manufacturing Systems (FMS) were even less useful with two thirds of the sampled companies who had introduced FMS reporting low or negative payoff to date. Return on investment in robotics was even lower. The survey covered a wide range of companies and the results should only be surprising to those managers who are readily impressed by new technology for its own sake and pretty pictures. The benefits of Computer Aided Design (CAD) and Computer Aided Manufacture (CAM) have been seriously oversold in the general engineering market place.

There are significant benefits to be obtained from CAD and CAM and its more recent derivative Computer Integrated Manufacture (CIM). However, these have to be worked for and do not automatically drop out of an investment in CAD/CAM technology. The Aerospace Industry has always been in the forefront of the development and exploitation of computer applications and because of their size, range of activities and expertise, Aerospace Companies have probably had more benefit from CAD/CAM than most other industries. Even in the Aerospace Industry the benefits have been restricted to a few areas and have probably not provided the productivity improvements predicted in the early days of CAD/CAM implementation.

Whilst productivity benefits have been realised slower than expected, as the systems increase in capability and become more widely used within a company, significant benefits are being achieved. A recent analysis within British Aerospace, Warton, has shown that average manhours to produce a drawing or document has reduced from 70-80 hours to a figure approaching 40 hours (ref. 2) over the last 10 years (after compensating for the different size of drawing etc.).

Similarly, CAM has made substantial improvements in productivity. These benefits have generally in the past been restricted to relatively small areas of the Company as the CAD systems created "islands of automation" for surface line definition, detail design and draughting, structural analysis and optimisation and N/C programming. The improvement in productivity in a relatively large area such as a drawing office may in theory be reflected by an increased work throughput or a reduction in manning. In practice it is difficult to reduce manning at the required rate and this may not be desirable since one of the benefits which CAD offers is to reduce design time spans and provide a design office more responsive to change and new products. However, if manning is not reduced in these "islands" then the increased work throughput capacity is out of balance with the rest of the organisation which has not become more productive. This lack of balance creates its own inefficiency which tends to negate any productivity gains that could have been achieved. Alternatively management is faced with the brave decision to increase the manning in the areas of low productivity to create the balance. This in itself does not seem a sensible way to go although it may be justified in the short term if there is a significant increase in predicted workload.

If CAD/CAM has not, and in the way it has evolved is unable, to produce the substantial productivity benefits which were claimed when it was introduced, then how can the return on investment be improved and are there signs that this improvement is likely in the near future ?

The main benefits to date from CAD/CAM have been seen in the manufacturing area. These benefits have arisen from the capability to transfer geometry data from design in a form which Production Engineering can extend/modify and of course from automation of manufacturing by numerically controlled machine tools.

Whilst one of the benefits is to transfer geometric data from Design to Production Engineering, this is rarely as efficient as it might be. Most good CAD systems have a relatively rudimentary N/C package added apparently as an afterthought at the back end and most good N/C packages have a basic but relatively inefficient geometric design package at the front. Hence many companies use separate design and N/C packages with an IGES (Initial Graphic Exchange Standard) neutral file interface between them. British Aerospace have always placed great emphasis on this major interface area between Design and Production and for 3 axis machining B.Ae, in conjunction with MCS (Manufacturing and Consulting Services Inc.), have developed the N/C machining package N/C COMBO as a fully integrated extension of the ANVIL 4000 design system. This has recently been extended by B.Ae to include control of automated inspection machines. However, for complicated 5axis machining we still use a specialist machining program APT NMG[2] (or BASIS[3] as it is marketed in the U.S.A.) via an IGES interface from ANVIL 4000.

British Aerospace has also been at the forefront in the integration of the manufacturing processes. There are 90 numerically controlled machines in the Warton Production unit with 48 of these having direct data communications with the main N/C database. The N/C database itself has been made machine independent by the use of a generalised post processor standard (BAEGEN) promulgated by British Aerospace via British Standards Institute (ref. 3). This allows N/C machine cutter location files to be post processed to a standard level and any machine specific limitations or additions are the responsibility of the individual machine controller software. This gives great flexibility in day to day production since a job can be transferred between machines to suit the workload without having to post process and tape prove on each machine. The N/C database is linked to the Company ordering system via a work scheduling file to match machining output with the delivery requirements. This system works well for small batch production but has not until very recently had a significant effect on the time taken to programme the machine and prove the machining process (tape proving) for production of the first unit.

2. CIM - THE FUTURE

Our expectations of CIM are:-

- reduction in project and manufacturing elapsed times.
- reduction in unit costs.
- reduction in reaction time to change.
- improvement in quality.

If "islands" of higher productivity created by the introduction of CAD/CAM create a lack of balance in a company and so do not result in an overall increase in efficiency then the only sensible alternative is to bridge between the "islands" and spread the technology and potential benefits across all areas of the company to recreate the balance.

This solution requires a particular dedication to examination in detail of the nature of each data interface and the techniques used for handling the data on each side of the interface. Examination of a few sample interfaces between different departments and even between sections within a department very quickly shows that the flow of information is not always well controlled or that there is confusion about the issue level of the data, it may be in the wrong form, it may be incomplete. Considerable manual effort goes into the handling, checking, conversion and in some cases regeneration of data on each side of an interface even when the data is incorrect.

Such considerations inevitably lead to the concept of a single database containing a complete, up to date and unambiguous set of data relating to a particular aircraft, with everybody having immediate access to the database via their own

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1. ANVIL 4000 is the trademark of MCS (Manufacturing & Consulting Services Inc.)
2. APT NMG is the trademark of B.Ae P.L.C.
3. BASIS is the trademark of CIMCO (Computer Integrated Manufacturing Company).

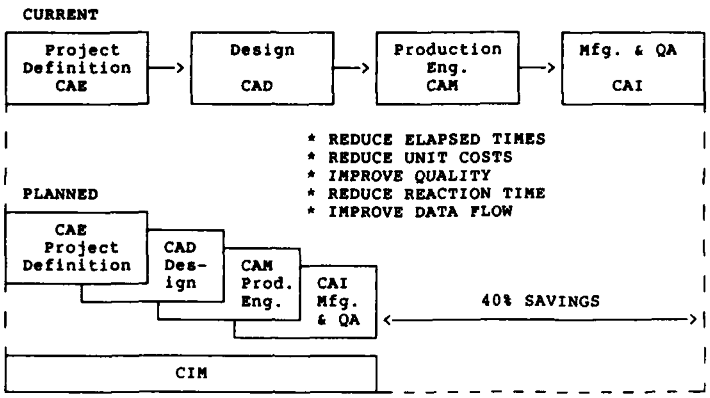


FIG. 1 - TIME REDUCTION THROUGH COMPUTER INTEGRATION

access routines which convert and present the data in the manner they require. This apparently simple statement has a large body of technical and administrative problems hidden within it and these will be discussed in more detail below. Suffice for now that the benefits of such a database have been assessed in terms of a reduction in elapsed timescales caused by everybody having the data they need available in the right form at the right time. This allows stages of work, which are currently carried out consecutively to overlpa (see Fig. 1). Once this occurs downstream activities can more readily feed back into the earlier design processes to ensure that the data received downstream conforms to production requirements. An overall reduction of 40% on elapsed time is planned for within British Aerospace from this integration and data control.

2.1 An Integrated Product Database

The requirement for a database to be unique in that data is only held once is often taken to mean that there needs to be a single relational database. This is not the case and it is doubtful whether any relational database system currently available has the speed of performance to handle a product as large as an aircraft. Data being held once only also implies that a change in any data should result automatically in changes in any other data derived therefrom (or at least in a warning that the data may no longer be valid since automatic uncontrolled changes of data may have unforeseen and catastrophic consequences).

A number of databases tailored to specific applications and which can be managed locally is desirable from such considerations as efficiency of data storage, interfacing with specific user application programs, speed of performance when available to a large number of users. Special databases would be developed for such topics as airborne software, assembly models and detail drawings, standard parts, tooling, project database communicates with these satellite batabases and maintains a central index which can point to and hence provide access to data and its status in any of the satellites. Such a Project Database is being established at Warton, initially for technical information only on the Eurofighter Project using the IBM DB2 database and DCS access control system. The specification and implementation of a complete product database structure is still one of the greatest areas of unknown in CIM. One of the major difficulties in implementing a common database is that of ensuring that people obtain the information related to their particular requirement - the most recent information is not always the information that is needed, for example Production may be working on data relevant to one batch of aircraft whilst Planning is producing data for the next batch and Supply Department may be looking for long lead time items on a batch which is still in Design. Thus up to date information needs qualifying as relevant current data.

2.2 Unambiguous Data

A person obtaining data from the database has to be able to interpret the data in one way only. Since people are generally fairly good at interpreting incomplete or inconsistent data but computers are generally poor, it is of more importance that the data used by computer applications programs have a unique consistent understanding. The conventional two dimensional drawing

requires experience and skill to interpret and even then mistakes are made in interpreting what a designer meant. Consequently 3D geometry is seen as an essential requirement for successful implementation of CIM. There are programs available which will convert from conventional 2D orthogonal views but these are of limited application (Ref. 4).

There is a choice of three dimensional models which can be used. Principally these devolve into wire-frame model, surface model, facetted solid model or true analytical solid model. Ideally we would use a true analytic model for all the design since this is the most complete description of the geometry. However, there are differences in creation time, data storage, computational power requirements and even feasibility for the more complex models. Generally the wire-frame model is insufficient in clarity. Wire-frame with surfaces is sufficient for visualisation of components and assemblies and is relatively low on computational power. However, where the computer needs itself to understand the geometry - as for example in the automated N/C machining direct from the geometric description - a solid model with the capability of boolean algebra is essential. A facetted model is fast and relatively cheap on display but the accuracy of a true analytic model is required for analysis. Thus the data stored should be of a true analytic model or a wire-frame with surfaces.

2.3 Data Access

The data needs to be available and easy to locate by a wide range of users. This probably involves an "intelligent" front end access system for the database which guides a person to the data. It certainly involves providing the same information to different people in different ways. This involves fast on-line transformation of the data. For CAD/CAM data this can involve a high computing power requirement which needs to be recognised in the early stages of justifying a common database system.

3. TRANSITION - THE PRESENT

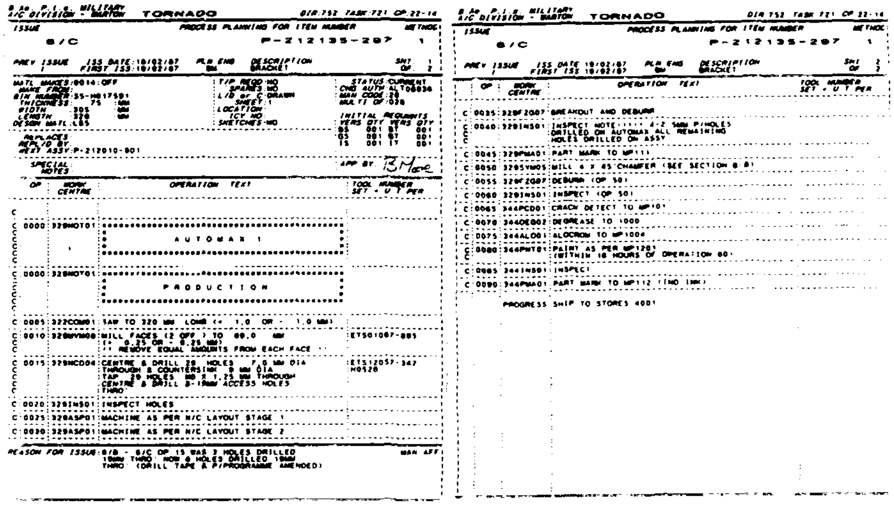
British Aerospace, like many other Aerospace Companies, is currently going through the stage of transition between CAD/CAM and CIM. The timing of this transition has to a large extent been determined by the trade off of cost and performance of hardware:-

- speed of computer processes for large database handling tasks with associativity of data. There are many who would argue that relational databases are still not fast enough for the workload envisaged on a Project Database.
- cost of computer processors to handle the massive interactive processing required by widespread use of solid modelling.
- graphic processors closely coupled to a terminal display (either in intelligent terminals such as Tektronix 4129 or IBM 5080 terminals or in engineering workstations like APOLLO or SUN) to give the speed of response necessary for handling large graphic data files.
- networking capabilities to allow easy transfer of data between computers of different manufacture and between systems and manufacturing cells. The initiatives of MAP, TOP and ISO networking standards are recent and still not fully developed.

However, computing costs are still falling at about 25% per annum and power is increasing with even the DEC mini computers now reaching powers of 50MIPS and work stations putting 4MIPS at a single engineers desk to the consternation of the DP managers. The rate of change of hardware capability is so great over the last three years that software development and application development seem to be struggling to keep pace. In this changing environment it is necessary to minimise costs and risks but choose and integrate the best current system for each application. Certain key implementations are already in progress and others are being evaluated by British Aerospace. Some of these are described below.

The major implementation already in operation is a Flexible Manufacturing System (FMS) for small steel, titanium and light alloy prismatic parts. This comprises an automated machining cell which contains six Automax machines for prime machining, two machines dedicated to preparation of material billets, two automated LK inspection machines together with automated goods vehicles for automatic transfer of materials, components and cutters and robotic handling/transfer of these items. This system is linked to the factory ordering system via a database control program which selects, checks the status of, and assembles all the data required to manufacture a component. This provides a fast, responsive system for manufacture on a "Just in Time" basis which is ideally suited for production of prototype components.

A similar, highly automated, FMS under development for sheet metal, flat and formed parts. This will be introduced towards the end of 1987. This will produce 50% of the detail parts going through the factory.



B Ae. P.L.G. MILITARY A/C DIVISION - WARTON   TORNADO   DIR 752 TASK 721 CP 22-14

ISSUE: B/C   PROCESS PLANNING FOR ITEM NUMBER P-212135-287   METHOD 1

PREV ISSUE 1   ISS DATE 10/02/87   FIRST ISS 10/02/87   PLN ENG BM   DESCRIPTION BRACKET   SHT 1 OF 2

MATL MAKES 0014 OFF   MAKE FROM   BIN NUMBER 55-H017591   THICKNESS 75 MM   WIDTH 305 MM   LENGTH 320 MM   DESIGN MATL L85

T/P REQD NO   SPARES NO   L/D or C DRAWN   SHEET 1   LOCATION   ICY NO   SKETCHES NO

STATUS CURRENT   CHG AUTH ALT08036   MAN CODE 28   MULTI OF 028

INITIAL REQUMNTS

VERS	QTY	VERS	QTY
BS	001	BT	001
GS	001	GT	001
IS	001	IT	001

REPLACES   REPL/D BY   NEXT ASSY P-212010-801

SPECIAL NOTES   APP BY B Moore

	OP	WORK CENTRE	OPERATION TEXT	TOOL NUMBER SET - U T PER
C				
C	0000	329NOT01	AUTOMAX 1	
C	0000	329NOT01	PRODUCTION	
C	0005	322COM01	SAW TO 320 MM LONG (+ 1.0 OR - 1.0 MM)	
C	0010	329MVM08	MILL FACES (2 OFF) TO 80.0 MM (+ 0.25 OR - 0.25 MM) ** REMOVE EQUAL AMOUNTS FROM EACH FACE **	ETS01087-885
C	0015	329NCD04	CENTRE & DRILL 28 HOLES 7.0 MM DIA THROUGH & COUNTERSINK 9 MM DIA TAP 28 HOLES M8 X 1.25 MM THROUGH CENTRE & DRILL 8-19MM ACCESS HOLES THRO'	ETS12057-347 H0528
C	0020	329INS01	INSPECT HOLES	
C	0025	329ASP01	MACHINE AS PER N/C LAYOUT STAGE 1	
C	0030	329ASP01	MACHINE AS PER N/C LAYOUT STAGE 2	

REASON FOR ISSUE: B/B - B/C OP 15 WAS 3 HOLES DRILLED 19MM THRO' NOW 8 HOLES DRILLED 19MM THRO' (DRILL TAPE & P/PROGRAMME AMENDED)   MAN AFF

B Ae. P.L.G. MILITARY A/C DIVISION - WARTON   TORNADO   DIR 752 TASK 721 CP 22-14

ISSUE: B/C   PROCESS PLANNING FOR ITEM NUMBER P-212135-287   METHOD 1

PREV ISSUE 1   ISS DATE 10/02/87   FIRST ISS 10/02/87   PLN ENG BM   DESCRIPTION BRACKET   SHT 2 OF 2

	OP	WORK CENTRE	OPERATION TEXT	TOOL NUMBER SET - U T PER
C	0035	329F2007	BREAKOUT AND DEBURR	
C	0040	329INS01	INSPECT NOTE:- 4-2 5MM P/HOLES DRILLED ON AUTOMAX ALL REMAINING HOLES DRILLED ON ASSY	
C	0045	329PMA01	PART MARK TO MP111	
C	0050	329SVM05	MILL 4 X 45 CHAMFER (SEE SECTION B-B)	
C	0055	329F2007	DEBURR (OP 50)	
C	0060	329INS01	INSPECT (OP 50)	
C	0065	344PCD01	CRACK DETECT TO MP101	
C	0070	344DEG02	DEGREASE TO 1000	
C	0075	344ALO01	ALOCROM TO MP1004	
C	0080	344PNT01	PAINT AS PER MP1201 (WITHIN 18 HOURS OF OPERATION 80)	
C	0085	344INS01	INSPECT	
C	0090	344PMA01	PART MARK TO MP112 (NO INK)	

PROGRESS SHIP TO STORES 4001

FIG. 2 - COMPUTER AIDED PLANNING INSTRUCTIONS

Upstream of the FMS cells the project timescales and costs have been reduced by the introduction of Computer Assisted Process Planning (CAPP) (Fig. 2). This reduces the workload in Production Engineering by providing a system which holds planning data in another database and thus allows existing planning for a similar part to be retrieved, edited and issued. An obvious step forward is to use a Coding and Classification system to assist in identifying similar parts. Such a system has already been produced for cutting tools and it is anticipated that this will result in savings of about 15% per year.

At the design end greater use is being made of 3D design using NAVIL 4000 (Fig. 3) and CATIA[1] for better visualisation of the design and solid modelling using CATIA is being used for concept design studies and "theoretical" installation mock-ups such as cockpit layouts (Fig. 4) and pipework configurations. The timescales and cost of components are also being reduced by means of an expert system to aid designers on the selection of the best design for manufacture.

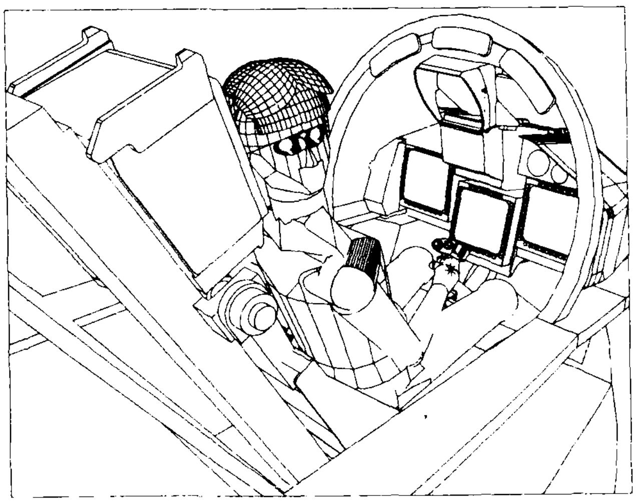


FIG. 3 - CONCEPT DESIGN (CATIA)

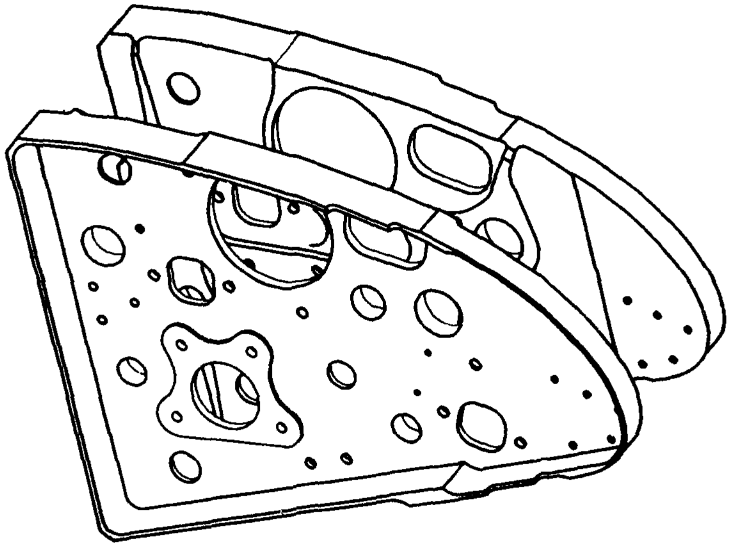


FIG. 4 - 3D DETAIL DESIGN (ANVIL 4000) FROM NMG SURFACES)

Less well developed is integration of the aircraft systems engineering with design and manufacture. However, progress is being made in this area with hydraulic and fluid systems being schemed at a CAD graphic terminal using a derivative of the BCAWD[2] system for electrical wiring diagrams. An automatic data extraction feature in the program selects and transfers the system design to a separate software package for performance analysis of the system (Fig. 5). The eventual aim is to integrate these two programs to give interactive analysis of different system configurations with the data there already in the form for detail design when an optimum solution is agreed.

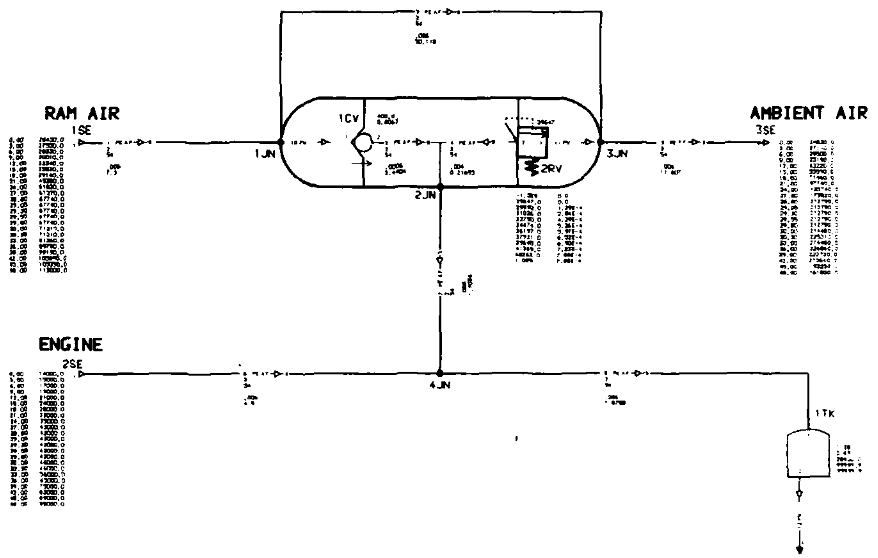


FIG. 5 - FUEL VENT SYSTEM SCHEMATICS (BCAWD)

1 CATIA is a trademark of Dassault Systemes.

2 BCAWD is a trademark of B.Ae P.L.C.

The automatic data extraction from the drawings has been developed for BCAWD for wiring and equipment data to provide reliable and early information to the electrical planning system BCAPE. This will again result in data being available faster and will reduce the timescales for design and manufacture of systems in line with the structure of the aircraft.

In addition to the Flexible Manufacturing Cells referred to above, a number of new machining centres are being established in 1987 and 1988. The timescales for developing and proving N/C control data and for synchronising the activities of several machines in a centre will be reduced by automatic generation of machine control data and by work using GRASP[1] is currently being carried out to demonstrate multi axis movement and access and the first steps have been taken towards automating N/C machine programming within a billet preparation area of the small parts FMS.

CONCLUSIONS

Reductions in timescale and cost for design and production of the prototype aircraft and components are being addressed on a broad front at British Aerospace within the control of Computer Integrated Manufacturing.

An objective of 40% reduction timescales has been set within British Aerospace (although in reality these timescales are often dictated by the customers). Much of this reduction results from better conceptual design facilities and more flexible approaches to production which enable computer control of manufacturing to be used on one off components. These require better, more responsive and reliable support systems than are currently available. In particular a 3D geometry database accessible quickly and providing data in the form required by users throughout the Company offers significant benefits.

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MINIMIZING DEVELOPMENT FLIGHT TEST TIME AND COST IN THE U.S. AIR FORCE

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SUMMARY

Flight testing has undergone some major changes in the past 20 years. The largest single technical change, the need to evaluate software-intensive systems, resulted from advances in computer technology. Test management concepts have changed as well. These changes were driven in part by technology and in part by a need for the Air Force to become more involved early in the test process. Today's avionics systems present both a quantum leap in capability and a quantum jump in test requirements. With workload growing both in magnitude and complexity, the challenge is to meet the increased demands cost-effectively and safely. For software-intensive systems, a ground-based simulation dedicated to the support of the flight test program is essential. This paper summarizes today's methods of operation which are geared to minimizing development time and costs. The focus of this process is on productivity--doing the right testing in the proper sequence in the most efficient and safest possible manner.

INTRODUCTION

The United States Air Force Flight Test Center (AFFTC) conducts aircraft development flight tests. Nearly every new United States Air Force airplane in the past 40 years was tested at Edwards, as were NASA's high speed flight research vehicles. The Edwards Flight Test Range is used to support these flight test programs. The Center also operates the Utah Test and Training Range, the Air Force's largest overland range where remotely-piloted research and test vehicles, plus air and surface-launched missiles, are tested. Edwards Air Force Base today is the hub of a tri-service test complex which encompasses several inland and overwater ranges throughout the southwestern United States.

The last 30 years have seen dramatic changes in aircraft technology and in the tools we use in flight testing. Aircraft flight envelopes, however, have not changed significantly in the past three decades. Fighter aircraft were approaching Mach 2 and 50,000 feet 30 years ago. Today, with a few notable exceptions, we are still dealing with a 50,000 ft/Mach 2 envelope. However, there have been significant improvements in flying qualities, and in subsonic thrust and lift-limited envelopes. In the late 50's, the 1960's and the early 70's, there were numerous new aerodynamic designs. In the early 70's alone, first flights were made on the following aircraft: the F-15, F-16, F-17, A-9, A-10, YC-14, YC-15, and B-1. The 70's were the era of competitive fly offs as well (A-9 vs A-10, F-16 vs F-17, YC-14 vs YC-15, AGM-86 vs AGM-109). Until the T-46 made its first flight in 1985, the most recent first flight on a totally new Air Force aircraft was the B-1 which flew in 1974. For the past ten years, flight testing at the Air Force Flight Test Center has been confined to derivatives of existing aircraft, primarily in the area of avionics upgrades.

The most significant change, by far, in the last 30 years, is the burgeoning use of software-intensive systems. In the past five years in particular, the world of on-board computer technology has been moving in maximum afterburner.

Air Force developmental flight test management concepts have undergone a similar evolutionary process. Technology has been the catalyst for many of these changes. The flight test and evaluation programs conducted on U.S. Air Force aircraft have gravitated over the past two decades from what were largely independent, sequential test programs conducted by the contractor, Air Force development and operational test agencies, to programs conducted on a concurrent basis from a single test location, Edwards Air Force Base.

The increase in software testing has resulted in a quantum jump in workload. The best single measure of workload at the Air Force Flight Test Center is test flying hours. The test workload has increased dramatically in recent years. In the past 6 years, test flying hours tripled. In fiscal year (FY) 1980 about 1870 test hours were flown from Edwards. In FY 1986, the number was 6000. The largest contributors to the workload are the F-15 and F-16 fighters and B-1 bomber testing. The test flying hour estimate for FY 1990 is 11,600. This is firm, on-the-books workload. There has always been a significant amount of additional test work that is not identified years in advance. 1985 and 1. 6 were Edwards' most successful years in terms of flight safety. More test hours than ever were flown without a single Class A mishap. Class A mishaps are accidents involving the loss of a test aircraft, a fatality, or more than $500,000 worth of damage.

TEST PROGRAM MANAGEMENT

The cost and complexity of today's test aircraft and ground support equipment, test range data acquisition equipment, data processing systems and test support ("chase") aircraft, were major considerations in the consolidation of test activities. Another ingredient, the need for increased visibility by the customer during the development process, combined with the prohibitive expense of duplicative testing, led to what is referred to in the Department of Defense (DOD) as combined testing.

Air Force implementation of this DOD policy emphasizes consolidation of test events wherever practical. Data from each test event are made available to all appropriate agencies using Air Force Systems Command facilities and capabilities, including instrumentation, data processing and analysis systems, to the maximum extent practical.

The management concept used for today's Air Force flight test programs is referred to as a Combined Test Force. It is a sophisticated application of matrix management principles. The typical Combined Test Force is composed of participants from the development organization (contractors), buyer, using commands and supporting commands. The contractor contingent may involve a prime contractor and subcontractors or as in the case of the B-1, a group of associate contractors (airframe, engine, offensive and defensive avionics) with the government as the integrating contractor. A comprehensive treatment of Combined Test Force operations is contained in reference 1. Salient points are summarized below.

In the Combined Test Force approach, test activities are combined to the maximum practical extent.

a. Participants are housed in common facilities.

b. The test aircraft are instrumented to meet the needs of development testing (contractor and Air Force) and operational testing.

c. A single test plan is developed which integrates and prioritizes test requirements.

d. Test range requirements are identified.

e. Combined aircrews are used for most missions in multiple place aircraft. In single seat aircraft, either contractor or Air Force development pilots fly envelope expansion missions.

f. Aircraft are located at a single site and maintained by an integrated maintenance team.

g. All test data are included in a common data base which is available to all team members.

h. Analysis and reporting of the test results is accomplished by each organization independently.

The most significant advantage to combined testing is the opportunity for an early and continuous look at the product by both the developmental and operational military communities. There is no substitute for hands-on experience. Early involvement by users provides an opportunity to influence the design where appropriate to improve the mission capability of the aircraft or system. Early participation in the test effort by military pilots, engineers and maintenance personnel helps identify problems before the production cycle is too far along.

Another advantage of combined testing is the reduced time and cost. Combined testing virtually eliminates the duplication which existed in the past when each tester used his own facilities and completed his own test and evaluation with little or no input from the other testers. If all team members participate in the planning effort, agree with the test approach and instrumentation and data collection methods, there is no reason to duplicate tests.

Consolidating all test aircraft at a single location has distinct cost saving benefits. More flexibility in the use of the aircraft is possible if they are instrumented correctly. When one test series is delayed, another test can be scheduled on the same aircraft. As a result, fewer instrumented aircraft can accomplish the same amount of testing than is possible if the aircraft are at more than one test location. Less support equipment is required, which is particularly significant when ground support equipment is scarce.

For military test programs the location should be a government facility in most instances because hanger, office and laboratory space will support successive programs with minimum investment after the original outlay. Making capital investments in facilities that can be used again is more cost effective than paying for contractor facilities that may only be used for a single program.

Facilities and equipment such as instrumented ranges, mission control rooms, data reduction facilities and weapon delivery ranges will also support several programs at the same time. Range facilities necessary for evaluation of fighter and bomber aircraft such as air-to-air and air-to-ground weapon delivery ranges, low-level and supersonic routes, electronic combat ranges, and adequate restricted airspace are only available at government facilities. The disadvantages of shared use of a test facility is that data reduction equipment, telemetry, and ranges must be shared. This can create scheduling conflicts, but these problems are manageable.

Conducting combined tests at a government facility also offers the potential advantage of oversight by an experienced flight test management team. The Flight Test Center applies the expertise gained from managing a variety of weapon system test efforts to improve test effectiveness and safety.

SAFETY - TEST RISK REDUCTION

There are two fundamental objectives on any test program--to conduct tests efficiently and safely. The balance of this paper addresses test efficiency. It is worthwhile to focus briefly on safety as well. The Air Force development test safety record has improved dramatically over the years. More test hours were flown in 1985 and 1986 at Edwards than in any previous year, without the loss of a test aircraft. Figure 1 summarizes the fighter aircraft record over the years. It is worthwhile to explore the reasons for the improvement in safety.

There are basically two reasons: technology and management procedures. Telemetry gives test personnel the ability to monitor critical parameters in real time. But monitoring isn't enough. The system must be designed to minimize recognition time, to identify the proper corrective action, and to initiate the action. Recognition time is minimized by prominently displaying limit exceedances of critical parameters. The proper corrective actions must be defined in advance with the test conductor given the responsibility for notifying the pilot immediately. The above describes the real time element. Of more importance is the up-front planning process.

Several years ago, after several accidents and near-accidents, a decision was made at the Flight Test Center to establish a separate safety organization. The objective was to create a small organization with some degree of independence from the test managers. The organization was and is staffed by experienced pilots and engineers who are on rotational assignments. They have current experience and have a guaranteed "return ticket" to their parent functional organization. Civilian engineers are given a temporary promotion. The combination of a rotational assignment and temporary promotion attracts highly qualified individuals.

Every test program undergoes a rigorous safety review by project personnel and senior supervisors which is chaired by people from the safety organization. The review system brings to bear all expertise, government and contractor. The review process ensures that critical conditions are approached incrementally, in small steps. The safety track record is significantly improved in comparison with the past because of a concerted effort to consider the entire system. With today's complex aircraft, there is the potential for interaction among subsystems. A systems approach is taken during the safety review by including people from a variety of test disciplines in the review process. As an example, propulsion and flying qualities experts are included in the review of gun firing tests. Secondly, people who have been involved in tests of a given type (e.g., flutter, high angle of attack) on a wide variety of aircraft are a part of the review process.

Tests are categorized as low risk, medium risk, or hazardous based on the severity of potential hazards and probability of occurrence. Examples of tests which have demonstrated higher than normal risk include first flights, flight envelope expansion, flutter tests, high angle of attack testing, rejected takeoffs, and tests with explosive warheads. Minimizing procedures to prevent a mishap from occurring or to reduce the consequences of a mishap are developed for each test hazard. All hazardous tests are thoroughly reviewed by the senior staff and Flight Test Center Commander prior to accomplishment.

TODAY'S DEVELOPMENT AND TEST CHALLENGE - AVIONIC SYSTEMS INTEGRATION

The emphasis of this paper thus far has been on test managment issues. The focus will now shift to the number one technical challenge facing the development and test community - avionic systems integration.

As was noted earlier, there has been a marked decrease in totally new acquisition programs in the last decade (figure 2). Weapon systems are becoming increasingly capable, complex, and costly, so it isn't surprising that there are fewer starts, and within each program, fewer units are bought each year. Upgrading fielded weapons systems is becoming the dominant means of force modernization (reference 2). This has been apparent to the development test community as the workload emphasis has shifted from air vehicle envelope expansion and airworthiness to subsystem upgrades.

Costs associated with typical current generation programs are depicted in figure 3. The cost savings associated with decreasing the number of flights by identifying problems on the ground is shown in figure 4. Calculations are made in figure 4 based on an assumed savings of 20 aircraft months (see reference 3).

The cost savings and schedule compression are dramatic. In our illustration, the cost savings factor is about 20 to 1. This is a very conservative estimate, and is based on our experience with today's fighter aircraft. Other estimates are as high as 100 to 1 (reference 4). The bottom line is that the test managers must insure that adequate funds and personnel resources are invested in the simulation in time to have it up and operating to support the test program.

It is not surprising that the problems associated with the developmental flight testing of software-intensive military systems are common to the development of current generation commercial aircraft. References 5 and 6 document the Boeing Commercial Airplane Company's experience during the development of the 757 and 767. The references also address the issue of growth in memory requirements for commercial applications. The average growth from contract award to certification was a factor in excess of 2.0. Several of the summary statements from the Boeing experience are repeated below because they are directly applicable to our recent experience.[5]

> "Hardware should provide adequate reserve capacity for inevitable growth in software."

> "Changes are a way of life in digital avionics--must be allowed for in program schedules and plans from outset."

> "Simulators/simulations are absolutely essential to development of avionics equipment--for early definition of requirements, testing of design concepts and validation of final designs. Simulations must be started early, maintained particularly early in flight test, and be as representative of airplane/engine dynamics as practically possible at all times."

The conclusion is obvious: for software-intensive systems a ground-based simulation dedicated to the support of the flight test program is essential. The cost-savings potential mandates that the simulation planning be given a level of attention comparable to the flight test planning. The use of the simulation must be planned for early on and integrated into the flight test program, data reduction and spares support. The simulation must be as representative of the airplane as is practical.

The payoffs from the use of a simulation facility to support avionics testing are summarized below:

- Three-fourths of software problems are resolvable on the ground at a fraction of the cost of flight.
- A reduction in test flying hours which translates into a reduction of test costs and an acceleration of test schedules.
- The costly and inefficient fly-fix-fly approach is minimized.
- Ground testing is more efficient because the experiment is controlled, repetition of test conditions is rapid, simple.
- Flight test time is used more effectively by isolating/keying on risk areas and smarter profile planning.
- Flight test safety for digital control systems is enhanced.

CONCLUSION

In conclusion, these are exciting times at Edwards Air Force Base. Test workload has grown dramatically in the past six years and is projected to increase in the future. Combined testing has proven to be a viable test management concept. It eliminates duplication, reduces test time and cost, and provides for earlier military participation. Aircraft flight test emphasis has shifted over the past ten years from airworthiness/aerodynamics testing to avionics subsystem test and integration. Advances in weapons system technology have had other significant impacts on the test process. Today's test aircraft require the use of a ground-based simulation which is dedicated to the support of the flight test program. Flight test challenges of the future include the need for continued improvement in avionic systems test efficiency, and increased emphasis on the use of simulators and other ground test facilities to supplement flight testing.

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FIGHTER/ATTACK TEST AIRCRAFT

AIRCRAFT TYPE	TEST AIRCRAFT LOST	FIRST FLIGHT	TEST FLIGHTS	TEST HOURS
F-15	0	JUL 72	9,400*	13,250*
F-16	0	FEB 74	13,900*	17,800*
A-10	1	MAY 72	2,310**	3,480**
A-7	0			
F-4	1			
F-111	4	DEC 64		
1953 - 59***			INITIAL TEST PERIOD	
YF, F-100A	6	MAY 53	5/53 - 12/55	
F-101A	2	SEP 54	9/54 - LATE 56	
YF-, F-102A	2	OCT 53	10/53 - 5/55	
XF-, YF-, F-104A	11	FEB 54	2/54 - MID 58	
YF-, F-105B	1	OCT 55	10/55 - 3/60	
F-106A	2	DEC 56	12/56 - 6/59	

*AS OF JAN 87 **THROUGH 1977 ***FROM AFFTC HISTORIES, TEST-RELATED, SOME DID NOT OCCUR AT EDWARDS

FIGURE 1

NEW U.S. AIR FORCE FIGHTERS, 1940s-1990s[a,b]

DECADE	FIGHTERS DEVELOPED
1940s	P-47, P-51, P-59, P-61, F-80, F-84, F-86, F-89, F-94
1950s	F-100, F-101, F-102, F-104, F-105, F-106
1960s	F-4, F-111
1970s	F-15, F-16
1980s 1990s	ATF (DEVELOPMENT PLANNED)

[a]THIS FIGURE EXCLUDES FIGHTERS THAT ENTERED FULL-SCALE DEVELOPMENT BUT THAT WERE NOT PROCURED FOR INVENTORY; IT THEREFORE UNDERSTATES THE NUMBER OF NEW STARTS FUNDED IN THE 1940s AND 1950s.

[b]EXTRACTED FROM TABLE 2, REFERENCE 2.

FIGURE 2

TYPICAL TEST PROGRAM COST DATA

AIRCRAFT	TEST FLIGHT FREQUENCY (FLIGHTS/MONTH)	TEST AIRCRAFT OPERATIONS COST ($1000/HOUR)	FLIGHT TEST FIXED SUPPORT COST ($1000 MONTH)	PROGRAMMABLE CAPACITY (1000 WORDS)
CURRENT GENERATION FIGHTER	10	15	$1,500	300 - 700
CURRENT GENERATION BOMBER	5	50	$5,000	600 - 800
NEXT GENERATION FIGHTER	10	30	$2,500	1,000

FIGURE 3

COST SAVINGS - TYPICAL FIGHTER

COST OF FLIGHTS:	
(250 FLIGHTS) (1.25 HRS/FLT) ($15,000/HR)	= $ 4,687,500
LESS COST OF SIMULATION:	
(250 FLIGHTS) (1 HR/FLT) ($4,000/HR)	= $ 1,000,000
NET SAVINGS FROM REDUCED FLIGHTS:	= $ 3,687,500
(20 AIRCRAFT MONTHS) ($1,500,000/MONTH)	= $30,000,000
TOTAL SAVINGS: $3,687,500 + $30,000,000	= $33,687,500

FIGURE 4

IMPROVED FLIGHT TEST PRODUCTIVITY USING ADVANCED ON LINE DATA SYSTEMS

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SUMMARY

This paper highlights the improvements made over the last two decades in the methods used to gather, assimilate and process flight test data. It discusses the development cost reductions that can be realized from the use of real time data systems and real time analysis software and relates the use of today's powerful computing capabilities to the the V-22 program requirements. The paper briefly discusses the increased emphasis on the role of simulation in real time analysis procedures.

INTRODUCTION

The rate at which the development of any new aircraft can progress is a function of many elements. One of the most important is the ability to process and assimilate the large amount of data generated by todays complex, mission oriented test aircraft. If a concerted effort is made to plan and implement a rapid data handling capability, the flight test phase of the development program can be significantly expedited. In the 1960's the analysis of test data was predominantly a manual task, however, the advent of the digital computer has dramatically impacted the Industry and opened the door to new and innovative ways to optimize the data handling process.

The use of magnetic tape recordings, pulse code modulation (PCM) and telemetry has increased the number of measurements which can be recorded simultaneously on a test aircraft and consequently has driven up the volume of data that is available for analysis. Readers familiar with flight testing will know that the data handling, processing and analysis tasks have frequently caused 'bottlenecks' in the process of data assimilation. The Boeing next generation real time data system "ATLAS" is being specifically designed to alleviate this problem by providing improvements to the current computing capability and by conducting a major portion of the analysis requirements from all technology disciplines in real time. The realization of this goal will require a dedicated effort to extend the capability of the existing application programs and to incorporate the new real time analysis requirements.

Figure 1. V-22 Osprey.

The use of real time application software is particularly important on the Bell/Boeing V-22 Osprey flight test program, which will be referenced throughout this paper. The nature of the V-22 test schedule is such that there will be little time to

conduct testing in series, which means that provisions for multi-discipline testing have to be made. The tilt rotor concept compounds the problem, in that flight test planning is based on a highly productive flight rate while testing must be accomplished not only in the vertical take off and landing (VTOL) and airplane modes of flight but also at a finite number of rotor conversion angles. A large number of handling qualities, performance, structural and systems data channels are necessary because the V-22 is a new aircraft concept with:

- a new composite structure
- a new engine
- a digital fly-by-wire control system
- a new avionics suite
- a new airborne data system
- a new ground station

The current objective of recording all data channels on every flight has driven up the data transfer rate to 200K words/sec which exceeds the data system sample rate used on any previous VTOL flight test program. In all V-22 test disciplines we are placing considerable emphasis on improving the productivity of the data reduction techniques and as a consequence, on achieving an increase in testing efficiency.

This paper will describe the improvements made to the Boeing data system over the past twenty years and will emphasize the areas where development cycle cost reductions have been realized and where further reductions are anticipated. A selection of analytical programs that have been or will be available for real time analysis will also be discussed.

The development of the ATLAS data system at Boeing is being conducted in parallel with the development of a similar, compatible system at Bell Helicopters. All of the analysis capabilities described in this paper will be available at both V-22 contractors facilities.

THE COST OF FLIGHT TESTING

Before discussing the impact of real time data analysis on the cost of flight testing, it is informative to note the areas where program funds are spent.

There are five primary phases in the development cycle of an air vehicle:

1) Conception - (design go ahead)
2) Gestation - (full scale development/systems qualification)
3) Birth - (first flight) } = Flight Test
4) Infancy - (prototype testing) }
5) Graduation - (service acceptance)

Experience has shown that in order to have a successful program the two dates that must be "set in concrete" are the first flight date and the day the aircraft is handed over to the user. These milestones encompass the flight test stage of the program which is the last phase of the development cycle and is an area where schedule and cost improvement is expected to be achieved. In fact any program slippages prior to this period are invariably expected to be recovered in flight test, hence flight testing often becomes the program's saviour!

A cost profile for a typical air vehicle development program is shown in figure 2. This curve is based on normalized data from programs at both Boeing Seattle and Boeing Vertol. It is evident that a significant portion of the total program funds is spent in the flight test phase of the program.

It is important that the available funds are managed wisely since it is the rule rather than the exception that they are, at least in the opinion of the flight test department, usually inadequate for the work required. Inovative ways must therefore be found to ensure that testing is accomplished within budget constraints, because during the development cycle the inevitable "UNK-UNKS" (unkrown-unknowns) occur that have to be quickly rectified. In the process of rectification then can, it not carefully controlled, quickly deplete available funds.

In the past, many techniques have been implemented for improving the productivity and cost effectiveness in the design and manufacturing phases of air vehicle development. For example, computer aided design, automation of production lines and the introduction of design optimization programs. It must be stressed, however, that in spite of all our advances in automation, predictive analysis and simulation we have been unable to eliminate the need for an extensive flight test program if a superior product is to be the end result.

So the challenge for the flight test organization is to design as much flexibility

into testing procedures, data systems and analysis techniques as possible to allow engineers to respond quickly and efficiently to the unexpected circumstances that are bound to occur.

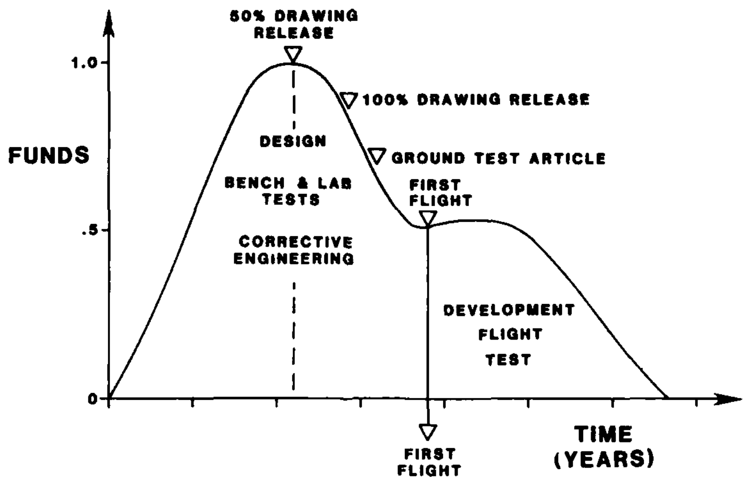


Figure 2. Cost Profile for Typical Air Vehicle

FACTORS AFFECTING FLIGHT RATE

In general terms "productive" is defined as the ability to complete a program within budget limitations, on schedule and having complied with customers specification and qualification requirements. To the customer this means a weapons system which performs its intended missions; this alone is the single most important measure of productivity. During the flight test program, however, the most meaningful indicators of productivity are the ability to resolve problems within cost constraints, on schedule, at a high productive flight rate and with the minimum amount of retesting.

The factors that directly influence schedule and flight rate are:

- Procedures for approval of ground and flight test releases and amendments
- Daily and periodic maintenance
- Requirements for changes and updates to aircraft configuration
- Instrumentation maintenance and recalibration
- Effectiveness of data system and analysis routines
- Weather
- The need to refly data

Two areas stand out where improvements can be achieved:

- Approval for testing
- The "fly-fix-fly" cycle, namely:
  - Aircraft maintenance/rework/refly
  - Data assymilation, processing and analysis

All flight test productivity improvements should be aimed at minimizing the fly-fix-fly cycle. This can be be accomplished by careful advanced test planning and efficient organization of manpower and resources.

For example, when testing military aircraft, the clearance procedures for envelope expansion, etc., must be established with the customer well before the safety of flight review for the aircraft. If the customer is not satisfied with the proposed arrangements, or requires a cumbersome review process, this in itself can become THE MOST significant program delay.

Delays during the flight test program are always expensive. Table 1 is an example of the hours spent at the Boeing Vertol Company (BVC) during recent programs on rework and maintenance. (This includes functional check flights and instrumentation rework). It can be seen that this is a significant portion of total program time. Figure 3 compares productive and total flight time for BVC flight test programs. The difference between the two curves, illustrates the reduction in non productive testing and an associated reduction in total flight time achieved as real time data monitoring and analysis have been developed. At Boeing, we believe that this can be attributed to the fact that flight safety and testing efficiency has been improved using real time techniques which in turn has reduced the need to refly for missed or unuseable data.

PROGRAM	% TIME SPENT ON MAINT/ REWORK
YUH-61A	35.0
CH-47FRB	30.8
CH-47D (3 A/C)	65.8*
MODEL 234LR	36.0
MODEL 234UT	47.4

* INCLUDES REFURBISHMENT AFTER AIRCRAFT ACCIDENT

Table 1. Time Spent on Maintenance and Rework.

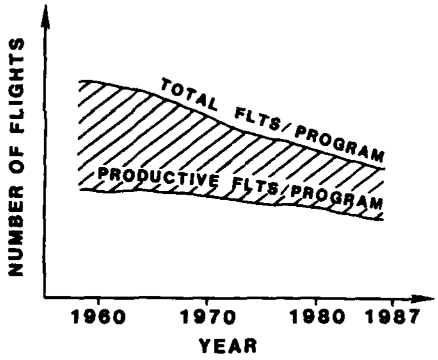


Figure 3. Relationship between Total and Productive Flight Hours.

The remainder of this paper will discuss the improvements made at Boeing Vertol to development cycle costs as a direct result of enhancements to the flight test data system and the extensive use of real time data analysis techniques.

THE VALUE OF REAL TIME DATA PROCESSING

The term "real time" can be misleading and therefore requires clarification. Ken Lunn, in Reference 1, defined it as follows:

"...within a time frame consistent with an orderly progression from test point to test point, within a single flight, with calculated engineering values to ensure flight safety and the validity of the test points flown."

Since no real time observation is truly concurrent with the observed event, the intuitive association of "real time" with an instantaneous observation is never accurate. For our purposes, it is a definition of the acceptable time lapse between an event, the observation of the event and the subsequent analysis or interpretation of the data consistent with the safe progress of testing. In general, final engineering answers are most valuable either during or immediately after a test. Early access to data allows for a rapid evaluation of aircraft configuration changes, quality of test conditions and for a comparison of actual versus predicted trends. This ensures that testing in the region of critical limits can be expedited with no compromise of flight safety or test control. Making data and predictions available during the flight and during the time the aircraft is being 'turned-round' can significantly improve testing efficiency as long as the data presentation is such that is makes rapid decision making possible.

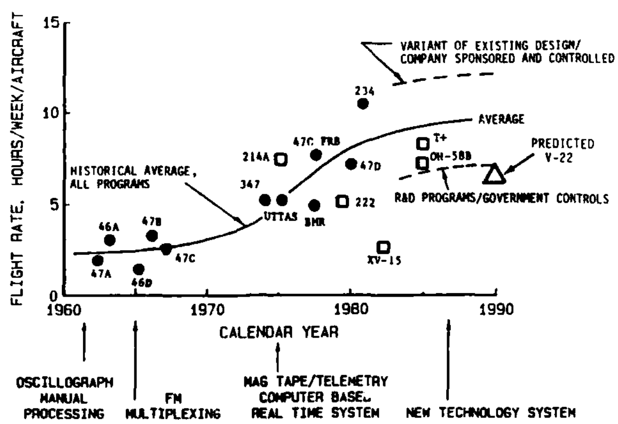
Consider, for example, the data processing task. The number of people needed to produce final engineering answers has changed dramatically over the past 25 years. Table 2 shows that today, with a staff of approximately 1/8 of the size of 1960 we can improve the data turn round by a factor of 15. These ratios will be improved still further using the new ATLAS data system.

DATE	AIRBORNE SYSTEM	GROUND STATION	TELEMETERED DATA	REAL-TIME PROCESSING	STREAMS	BATCH PROCESSING	TURN-AROUND TIME	STAFF SIZE	THRU PUT	GRAPHICS
c1960	RECORDING OSCILLOGRAPH	STRIPOUT	12-CHANNEL NBFM (PBW)	HAND ANALYSIS	—	PUNCH CARD INPUT TO IBM 650	3 WEEKS	40	MANUAL	NONE
1968	NBFM-MAGNETIC TAPE	AUTOMATIC ANALOG-TO-DIGITAL CONVERSION-CDC3100	12-CHANNEL NBFM (PBW)	HAND ANALYSIS	—	DIGITAL TAPE INPUT TO IBM 7044 IBM 360	1.5 WEEKS	20	N/A	NONE
1974	NBFM AND PCM-MAGNETIC TAPE	GRUMMAN AUTOMATED TELEMETRY STATION	ALL PCM-15-CHANNEL NBFM (CBW)	COMPUTER REAL-TIME ANALYSIS PARAMETER LIMITED	2*	DIGITAL TAPE INPUT TO CYBER 73	5 DAYS	10	60,000 W/S	LIMITED
1979	PCM MAGNETIC TAPE	BOEING STAR LAB	ALL DATA	COMPUTER REAL-TIME ANALYSIS: • STRESS • DYNAMICS • FLYING QUALITIES • PERFORM-ANCE	2*	INTERACTIVE FROM DISK FILES. NOT IN USE *DURING* TESTING. SINGLE/DUAL TERMINAL	< 1 DAY	6	50,000 W/S	1 TERMINAL FOR COMPUTER OPERATOR
1987	PCM MAG TAPE	ATLAS	ALL DATA	• COMPUTER REAL-TIME ANALYSIS MULTIPLE PARAMETERS DISCIPLINES	2	INTERACTIVE MULTI-TERMINAL	< 0.5 DAY	3	200,000 W/S	MULTI TERMINALS INTERACTIVE GRAPHICS WALL DISPLAYS

* NOT TOTALLY INDEPENDENT

Table 2. Evolution of Real Time Data System.

The benefits in terms of flight rate are shown in Figure 4. This shows a flight rate for the CH-47FRB program of 3 times the rate achieved in 1958. We are expecting a similar flight rate for the V-22. Close examination of Figure 4 shows a flattening of the trend curve into the 1990's. The reason for predicting the slightly lower productive flight rate than might be expected from the growth trend, is that there has been a tendency over recent years for the government to assume more control over the way prototype programs proceed, which has impacted productive flight time. By improving test techniques and data system capability it is possible to better committed targets. For example, the Boeing YUH-61A proposal targeted three and a half (3.5) productive flight hours per week; five (5) productive flight hours per week (the internal company target) were achieved. If a similar logic is applied for the more sophisticated V-22 program, we should achieve 30-35 hours per month.



CHANNELS PROCESSED IN REAL TIME	0	12	250 TO 500	UP TO 1500
CHANNELS PROCESSED BY BATCH	50 TO 150	120 TO 200	LIMITED	NONE
COMPUTER CAPACITY	-	CDC 3100 36 CHANNEL	XEROX E3 AND E9 50,000 WORDS/SEC	TELEDYNE/VAX 400,000 WORDS/SEC

Figure 4. Flight Test Productivity Improvements.

Table 3 presents a comparison of some fixed wing, military and commercial flight rates. Note the high rates achieved on the Boeing Commercial aircraft. These are a direct consequence of the commercial aircraft's extended range and onboard data analysis capability. The high flight rates result in short flight test programs, approximately 10 months for the 747 and 727 and 8 months for the 737. The V-22 is not likely to achieve flight rates to equal Boeing Commercial aircraft, but will match and hopefully better the monthly productive flight rates achieved on current military fixed wing aircraft.

ARCHITECTURE OF THE NEW BOEING DATA SYSTEM (ATLAS)

The current Boeing data system (STAR LAB) has evolved from oscillograph recordings, and Frequency Modulated (FM) analysis to the use of programmable pulse code modulated (PCM) digital telemetered data. Data analysis and presentation has progressed from slide rules and colored pencils to sophisticated laser printers and real time analysis. (Reference 2 gives a detailed account of this history).

The Boeing Company has been involved in 'real time' data aquisition since the early 1960's. Our first attempts involved the use of a CDC 3100 computer and our initial objective was to produce tabulated data thirty minutes after conclusion of flight testing. This data was then passed to the various engineering groups for detailed analysis and invariably took weeks to process thoroughly.

In describing Boeing Vertol's first generation real time flight test data system, which was developed as a result of using the Grumman Real Time system on the UTTAS program, reference 1 postulated future systems and stated:

"...the next generation of real time system should be built around a large mini-computer with the data processing handled by programmable digital signal processors (PDSP).

It should be possible to link any number of these PDSP's onto the stream so that concurrent parallel analyses- (e.g., stress analysis, harmonic analysis, and aircraft mode shapes) could be operating simultaneously. The total system should be loaded from the central processing unit CPU) and should house only the information that could be shared by multiple streams, such as aircraft calibrations. This CPU should collect the PDSP outputs and be able to input into the data base at any time, during or after a flight. Each real time data stream, with the exception of the data base shared files, should be independent of the other. Vertol operational experience with multiple data streams on a single processor ... has shown that the operation of one stream inevitably impacts the processing speed and reliability of the other."

	MODEL	TYPE PROGRAM	FLIGHT RATE (HR/MO)
BOEING SEATTLE	737	COMM-VARIANT	37 TO 74
BOEING SEATTLE	757	COMM-NEW AIRCRAFT	46.6
BOEING SEATTLE	767	COMM-NEW AIRCRAFT	54.1
GRUMMAN CALVERTON	F14	MIL-NAVY-RE-ENGINE	20.25
GRUMMAN CALVERTON	C2A	NAVY TURBOPROP	23.25
GRUMMAN CALVERTON	OV-10	USMC TURBOPROP	23.25
GRUMMAN CALVERTON	A6	JET-NAVY	19.5
GRUMMAN CALVERTON	G3	COMM-VARIANT	29.3
BOEING VERTOL	V-22	MIL-NAVY-NEW AIRCRAFT	25.0

Table 3. Comparison of Typical Fixed Wing Flight Test Rates.

The basic front end/processing part of the new data system at Boeing was designed and integrated by Teledyne and the system architecture conforms to the above recommendations. These "ground rules" have also been observed by Boeing Computer Services (BCS) and the Boeing flight test data group.

The system is shown diagramatically in Figure 5 and it's capabilities are documented in Table 4. Three Digital Equipment Corporation (DEC) Vax computers are used in conjunction with two Teledyne Real Time Processing Systems (RMPS). The Teledyne RMPS contains the telemetry "front end". (This is where data acquisition, data quality checks, stripchart D-A conversion, applications processing and data conditioning is conducted). Two independent processors are used to control real time graphics, software, messages and data switching. A third processor is used for the storage of instrumentation configuration calibration files and the processed aircraft data base.

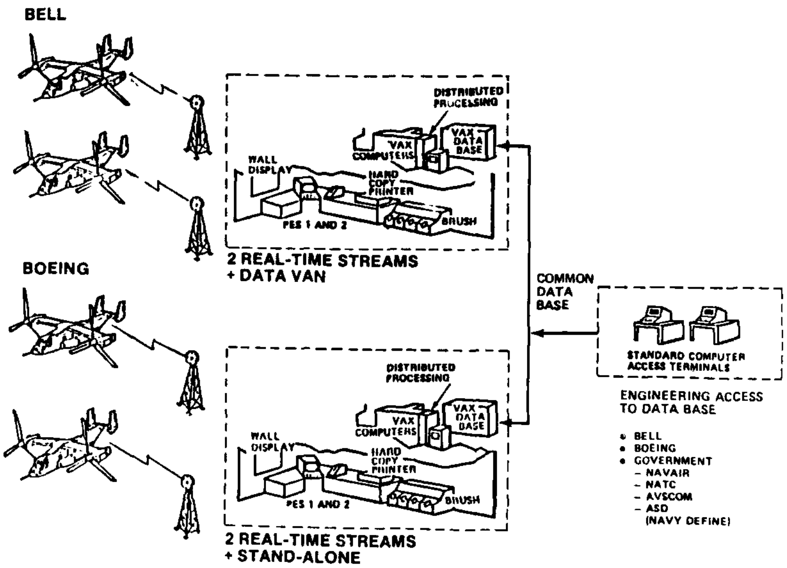


Figure 5. V-22 Flight Test Data System.

The ATLAS system is designed for "extendability" and "productivity" as follows:

> The VAX "star" cluster allows further DEC equipment to be added for "housekeeping" should additional CPU or data base storage be required, while the 68000 processors, which perform data processing and analysis can be increased by approximately three times.
>
> All functions of each real time data stream are separate and redundant so that neither stream affects operation of the other.
>
> The 68000 processors, are linked in such a way that priority analyses are allocated the correct amount of processing power while "left over" processing capability can be used for secondary analysis tasks.

This configuration increases productivity by eliminating any impact between data streams, (i.e. between two aircraft flying different programs) and reduces post flight processing by performing parallel analysis tasks during a real time monitoring operation on a single stream. Currently we do not have the peripherals to display the output from simultaneous parallel analyses. This is an option which could be implemented if we find that it would be cost effective, and would provide the capability to monitor two or more completely seperate analysis programs per flight if data from the two could be gathered from common flight manuevers.

The system sizing is such that for our projected requirements it will be possible to have all measured parameters available for analysis in real time on each stream up to 4096 measurements at a bit rate of 2 megabites. This data rate, combined with the much higher plotting and spooling capability will allow us to maximize our ability to analyze a significant portion of the required data in real time (ie during the flight).

For the V-22, the maximum number of measured parameters on a single aircraft will be approximately 1200 and this number, at the frequency response required for the envelope expansion aircraft defines the size of the data processing system. Table 5

presents a comparison of the number of parameters measured on Bell and Boeing development aircraft over the last 15 years. It is important to note that although we are recording more parameters than on previous programs we still expect to turn the data around faster with the new data system, and to be able to make critical decisions rapidly and with more confidence.

4	**PCM SAMPLE STREAMS OPERATING SIMULTANEOUSLY FROM A SINGLE AIRCRAFT**
100,000	**DATA SAMPLES/SECOND FOR ALL SOURCES DURING PROCESSING**
400,000	**DATA SAMPLES/SEC DURING FAST DISK SPOOL LOADING MODE**
10,000	**DATA SAMPLES/SECOND ON ANY SINGLE INSTRUMENT DATA CODE**
4,096	**DIFFERENT INSTRUMENT CHANNEL DATA CODES**
32	**STRIPCHART PEN OUTPUTS AT 300 DATA VALUES/SECOND MAX.**
256	**DISCRETE BIT OUTPUTS SELECTED FROM 16 PCM DATA WORDS**
128	**DATA CROSS PLOTS OF PROGRAM RESULTS WITH UP TO 128 TOTAL CURVES**
30	**MINUTES OF DATA PLAYBACK AT DESIGN SAMPLE RATE (100,000 SAMPLES/SECOND)**
8	**PROCESSING SENARIOS LOADED AND AVAILABLE**
1	**SAFETY OF FLIGHT OUTPUT STREAM WITH 10 VALUES FOR BAR GRAPH TYPE DISPLAYS AND 20 CURRENT OUT OF LIMITS VALUES. (RS232 LINE)**

Table 4. ATLAS System Capabilities.

The V-22 data rate is (200 K words/S), approximately four (4) times that used on previous flight test programs and, to be productive, we need to carefully plan the processing routines and techniques to avoid being "deluged" with data that cannot be assimilated in the proper time frame. Whether we will need to continue to transfer this very high data rate remains to be seen since the driver for the V-22 is the all composite structure. (The avionics suite and flight control system utilizes a separate recording and processing system on the V-22). As we learn more during envelope expansion it may be possible to delete some parameters.

With the advent of LHX the combination of an advanced avionics/weapons/visionics suite together with our desire to use one data system for all LHX data, will present an even greater challenge. The V-22 program will be a stepping stone and a learning block towards meeting this challenge.

In 1982 reference 3 suggested that "networking" our test and analysis facilities within the Boeing Company could increase data gathering and analysis efficiency. It stated in part:

"For the long range future, we are studying ways to tie in all our test and interactive design computers to merge and access all sources of information. We have, or will have ..... flight test, wind tunnel, simulation and structural test lab computers as well as a computer aided design system. The flight test system contains a data base which stores calculated values for flight loads for all recent programs. We are in the planning stages of extending this data base to other disciplines such as vibration and performance, etc. Since all predictive techniques involve "predic -test-modify-predict" cycles, if we could allow all our data sources to "talk" to each other we could speed up the refinement of our predictive technology."

PROGRAM	No. of PARAMETERS
HCMk 1	150**
CH-47D	250*
XV-15	350***
YUH-61A	500
V-22	1200

*MODERNIZATION PROGRAM
**OFF SITE ICING TRIAL
***PROOF OF CONCEPT

Table 5. Data Parameter Comparison.

Boeing Computer Services (BCS) have recently installed a "Boeing Vertol Campus" newtork which links all computers in the BVC engineering organization, except the Wilmington (Delaware) Flight Test Facility. The newtork will, with the activation of the ATLAS be extended to Wilmington.

The Boeing Flight Test real time data system will be 'tied in' with compatible systems at Bell Helicopters and the Naval Air Test Center (NATC). Commonality between the three systems will include algorithms, a common data base and an active data transfer link. Figures 6 and 7 show the planned Boeing Vertol Engineering Flight Test and V-22 team member networks. For the first time in the helicopter industry, it will be possible to access data at one test site from testing conducted at another, on the same day.

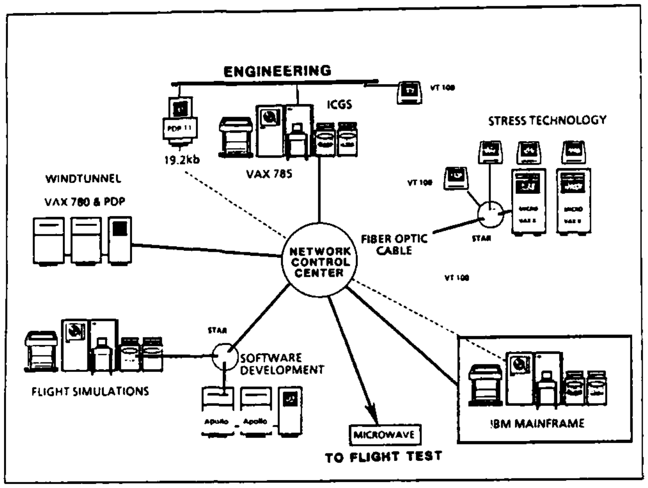


Figure 6. Boeing Vertol Computer Network.

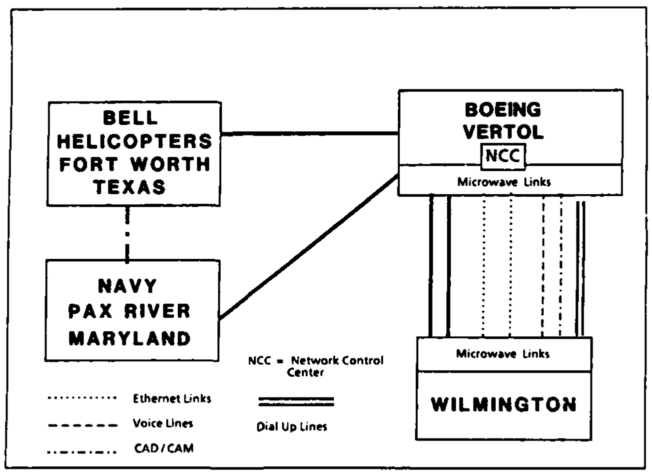


Figure 7. V-22 Data Communications Network.

REAL TIME PREDICTIONS

The prediction of airplane behaviour has historically achieved a greater degree of success than corresponding helicopter predictions, primarily because the fixed wing has the advantage of being inherently more stable and possesses a far less complicated lift generating device (ie., it does not have the complexity of high frequency dynamics that are fundamental to the helicopter). Although the V-22 operates in both airplane and helicopter modes there is not an easily defined split between the dynamic characteristics of the two modes. For reference it is useful to compare the helicopter

and fixed wing operating frequency spectrums. It can be seen (figure 8) that while the fixed wing spectrum is from very low frequency to approximately 12Hz (excluding engines), the helicopter, on the other hand, generates a whole range of resonances between .01Hz and say 70Hz. The V-22 characteristics span both regimes.

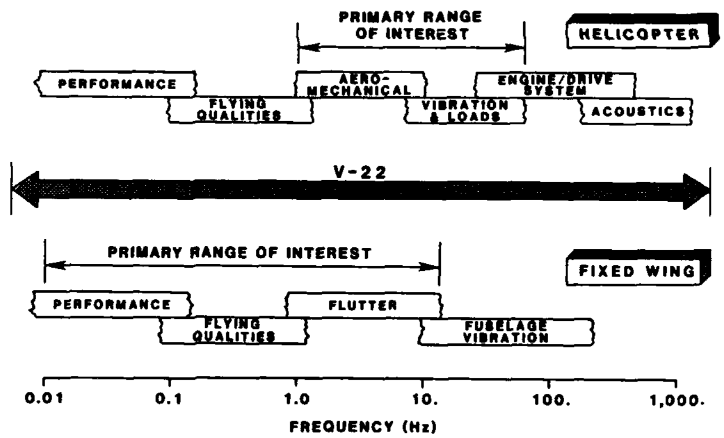


Figure 8. V-22/Helicopter/Fixed Wing Frequency Spectrum.

Before real time data analysis was available the degree of reliance that the test team could place on any type of prediction was limited, because comparisons with flight data could not be made until well after the fact. The introduction of better computing systems that could process data at very high rates provided the capability to produce engineering answers for comparison in almost 'real time'. However, this was limited to manual comparison - usually an engineer using the nearest window as a light table. Nevertheless, this was an improvement over the earlier capability, which increased the productive flight rate and decreased data turn round time significantly.

Historically (at least in the helicopter world) when monitoring tests in real time most attention has been given to flight safety. Application programs were developed primarily for improving test build up techniques to avoid accidents. It has become a standard in the aircraft industry that critical parameters be monitored in real time through the use of telemetered data to make test go-no go decisions. These decisions are made by engineers based on a review of the characteristics of critical test parameters in conjunction with qualitative comment from the pilot. With current data systems, it is normal to conduct detailed parameter comparison using time histories and cross plots of critical data, between flights, (at best), on the same day, or some time later dependent upon the analysis priority.

With the new Boeing data system we will maintain an equal vigil on flight safety but in addition various forms of prediction will be presented to the test team in real time. This will facilitate must faster decision making on the part of the team members and reduce the need to delay flights in order to compare data with off line predictions.

THE TOOLS AVAILABLE FOR REAL TIME PREDICTIONS

The new data system will have the capability to present various forms of analytical predictions for direct comparison with real time data.

The methods available for generating pretest predictions are:

- linear and non-linear mathematical models
- wind tunnel test predictions
- flight simulator testing
- static test/Bench test articles

To aid the decision making process, predictions from any of the above methods will be stored in the ATLAS computer data base and recalled for presentation to the test team DURING THE TEST MANEUVER, providing a direct comparison with flight data on a display directly in front of the responsible engineer. This will provide a safety of flight monitor in areas of high risk testing that will allow the critical decisions to be made with added confidence, especially as the test program progresses, as the flight envelope is expanded and updates to the mathematical models and simulators are made using actual flight test data.

Flight load survey testing is one area where displaying predictions to the test team will quickly tell the engineer whether it is safe, from a structural standpoint, to continue with the next, more critical flight condition. One of the main objectives of "predictive testing" is to aid the pilot in his effort to accomplish test objectives safely with a minimum amount of build up time required for each data condition.

It has been the normal practice at Boeing to analyze flight load survey and structural demonstration conditions after the test flight has been completed. This has sometimes resulted, after data is analyzed more closely, in the need for repeat testing because something about the way the maneuver was performed didn't match the specification requirement. The new Boeing data systems will have the capability to compare the pilot's control input and maneuver characteristics and to limit check critical parameters with the specification requirements in real time. A typical example is shown in Figure 9. Once the maneuver has been accepted by the engineer, plots of critical airframe bending moment distributions will be displayed and compared with predictions from analytical and static test article results. The analysis can be taken further. A summary plot of combined bending and torsion data can be displayed for each maneuver and compared with the aircraft's predicted design strength envelope.

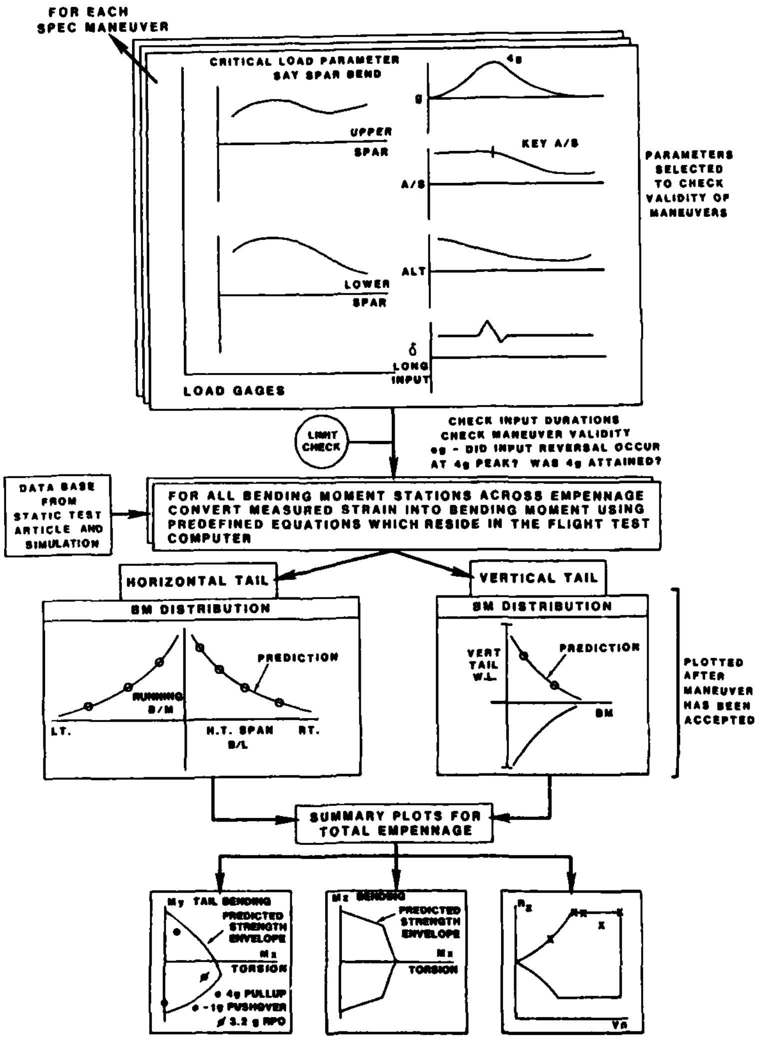


Figure 9. Predictive Testing for Horizontal Tail Loads.

The V-22 presents us with a tremendous challenge, in that methodology must be developed (or "borrowed" from applicable areas) to predict the behaviour of both the helicopter and the fixed wing characteristics of the aircraft. Bell-Boeing has already developed a generic tilt rotor math model that is the basis for the current V-22 simulations at both companies. This model, derived from earlier work on the XV-15 and extensive V-22 wind tunnel test, will be enhanced as V-22 flight test data is gathered. It will be used to support high risk test programs and to negate the need to fly "mundane" test points in the test article.

Typically, this type of prediction will be used to reduce the significant flight test risk involved in fixed wing testing such as high angle of attack and spin demonstrations and in the helicopter world, testing such as height velocity and autorotative landings.

TESTING WITH THE AID OF SIMULATION

The V-22 simulator and applicable engineering computers will be 'tied in' to the flight test data system as previously shown in Figure 7 so that data can be transferred between flight test, the simulator and engineering areas by the "push of a button", rather than making copies of tapes, and converting to formats compatible for transfer, as is necessary with the current data system set up.

Now that mathematical modelling techniques have been improved and time frames reduced to times that induce minimal visual or computational lags, simulation has become a meaningful prediction tool for support of flight test and pilot training.

Testing with the aid of simulation provides the following advantages:

- An early 'feel' for the aircraft's flying characteristics
- Risk Reduction
- Allows multi-pilot participation leading to improved flight test efficiency.
- Provides a more precise control of variables.
- Allows pilot training to be started prior to flight test.
- Saves Flight Test time and reduces cost.

Two recent tasks conducted on the V-22 simulator at Bell Helicopters highlight the significant savings that have already been realized during the design phase of the program from using the simulator as a design tool. The first, concerns development the multifunction cockpit displays that are driven by the aircrafts mission computers and are a derivative of an in service helicopter system. Extensive, relatively low cost simulator evaluations have been conducted in the optimization of baseline VSI and HSI pilot's displays for the V-22. This work has been completed in the "non pressure" environment of the simulator, saving significantly over the cost of similar development in flight test. In addition changes have been made early in the design process and have had minimal impact on display software and hardware development. The second task also concerns the use of the Bell V-22 simulator to develop piloting techniques prior to flight evaluations of the XV-15 power off reconversion characteristics, which were considered to present considerable flight test risk. Various techniques were evaluated on the simulator, and one was selected, that kept the critical rotor speed decay and aircraft attitude, altitude and airspeed excursions to a minimum. After training the pilots in this optimum technique on the simulator the maneuver was successfully repeated on the test aircraft without incident.

The accuracy of the XV-15 math model played a major part in the success of this evaluation. The model had been continually updated and compared with flight test data as it became available over the years, highlighting the need to optimize the V-22 model with simular urgency. An early update of the simulation model with flight test data will allow the test team to significantly reduce the flight time required to complete high risk test programs by evaluating flying techniques on the simulator first and substituting simulator based testing for non critical flight test data points.

As confidence in testing with the aid of simulation is developed, and future engineering mathematical models more closely represent the aircraft characteristics it is anticipated that, for some types of testing, the simulator will be brought on line during the flight test program to quickly investigate 'problem' points in the envelope prior to conducting the condition on the aircraft.

THE DEVELOPMENT OF ON BOARD DATA SYSTEMS

At Boeing Vertol testing has been streamlined by the use of on-board data systems for both the pilot and the engineer. The onboard data system was developed to provide the following advantages:

- To help the pilot set up test conditions, particularly when flying to "referred" test points

- To reduce the pilot-to-ground station communications

- To speed up the data taking process by providing the pilot with critical condition data

An onboard data system was used to great advantage on the HC-Mk1 Chinook icing program for a high priority requirement from the Royal Air Force to provide their Chinook fleet with an all weather capability in an ambitious two year off site de-ice system development and certification program. To achieve these goals it was necessary to develop a system that combined flexible de-ice system control with real time data analysis techniques and to provide an onboard decision making capability in the icing environment.

Onboard presentation of data to pilots had been developed at Boeing during the Model 234 program. These techniques were extended to provide the engineers, who flew on all HC-Mk1 Icing flights, with an onboard decision making capability.

Three primary categories of analysis were developed:

1) Performance
2) Flight Loads
3) Flying Qualities

The basic system concept was to provide the test engineer with icing to clear air data comparisons in each of the above categories in flight, which afforded the following advantages:

- It provided a real time capability that did not require telemetry. All safety of flight and development parameters were monitored onboard.

- It reduced post flight analysis by identifying small segments of recorded data for more extensive analysis.

- The capability to determine increments of rotor power and loads accelerated de-ice system optimization and was the primary reason that further development testing in a follow-on winter was not required.

- The fact that the data could be analyzed in real time without the need for ground station support provided increased test flexibility when used in conjunction with the aircraft's extended range capability.

- It gave the aircraft the essential freedom to search for icing conditions well out of the range of telemetry (especially at lower altitudes). The capability to totally calibrate the system onboard divorced the aircraft from the home base and allowed 'staging' in areas of potential or confirmed icing.

Similar onboard capability will be provided on the V-22 icing trials, and for other offsite requirements, where it can be cost effective.

THE USE OF REAL TIME APPLICATION PROGRAMS

The driver behind the use of real time application programs is the need to provide timely engineering analyses of data to:

- Augment the technology engineers decision process
- Minimize flight safety risks
- Optimize aircraft turnaround time
- Reduce the need for repeat testing
- Minimize the delays associated with new aircraft development

In 1981 Ken Lunn wrote in reference 3 .. "Although STAR LAB has developed (application) programs which are used by virtually all of the technology disciplines, we do not feel that these programs will be enough to keep the engineers satisfied with future testing and helicopter requirements".

This statement has proven to be prophetic, because, as the engineering community has become more aware of the power of the computer the engineers have become more demanding of its capabilities.

The V-22 program will significantly extend rapid near real-time analysis of large masses of data. In order to ensure that the data processing task supports the highly productive flight rate and fixed price costs, Bell-Boeing will draw upon the real time analysis programs developed at Boeing for helicopter testing since 1975. These will be the foundation for a new and more extensive capability for the V-22, LHX and other programs.

It is obviously cost effective to complete development and qualification in the shortest possible time. For example, on the V-22 program the flight envelope will be expanded incrementally until operating limits are established. During this process there will be planned investigations to optimize systems such as the digital fly by wire flight control system and also the unplanned investigations that are inevitable on a new aircraft.

Either type of investigation, whether planned or not, leads to decisions on configuration, which must be made quickly and confidently. We intend to accomplish this using "on-line" analytical capabilities. Application programs have accelerated the task of helicopter qualification at Boeing, and have certainly been a major factor in achieving the cost and schedule goals. New data systems are now capable of analyzing a much larger spectrum of data in real time, and must be complemented with sophisticated analysis routines that are conducted in, or near, real time in order to cope with the ever increasing demand for data.

The planning of real time analysis packages is already underway at Boeing and Bell Helicopters to support a June 1988 first flight date. This early start is necessary because the number of application programs will far exceed what we are used to from previous programs. When the V-22 flight simulator is "tied-in" with the flight test data network in 1988 we will have the capability to troubleshoot the programs using pilot-in-the-loop checkouts. The tie-in will be through data base access and we will optimize the simulation evaluation procedures to match those of flight test. This will ensure that the vast majority of flight test analysis software problems are identified and solved prior to flight test, where troubleshooting becomes a costly affair. The XV-15 will also be used to provide an early evaluation of the application software.

Table 6 provides a summary of application programs that are planned for use with the new data system. A comparison with the capability of the current STAR lab shows how Boeing will rely even more on real time routines for all the major technology disciplines.

Before detailing some of the techniques that are being developed by Bell-Boeing, two examples have been selected to illustrate the advantages of real time analysis.

On a new aircraft the aerodynamic, structural and performance tests are often carried out simultaneously at small increments in Mach/EAS until the design envelope is cleared. The mach number is not increased until the preceding tests have been analyzed and the results found to be satisfactory. On the XV-15 program in the 1970's it took two days to analyze aeroelastic stability data before the next test point was cleared for evaluation. This meant that only one speed per day could be analyzed and testing was held up until analysis had been completed. We will be able to analyze all of the critical V-22 aeroelastic modes in real time and proceed cautiously but quickly with envelope expansion until the envelope limits are reached. Critical decisions will be made in real time by reference to summary plots, of say, damping ratio versus airspeed for each critical control surface. It should be noted that the Boeing Vertol STAR Lab does have a "moving block" analysis which can process one critical parameter in about 1 1/2 minutes before clearing the aircraft to the next test point. The number of parameters analyzed and the analysis time will be improved with ATLAS.

An even more dramatic improvement in the processing time of contemporary data systems is highlighted when one compares the task that engineers had to perform to reduce data only a matter of 20 years ago with the same analysis conducted on today's sophisticated machines. This was the era when all data was reduced by hand, from pilots cards and using the "HAC" chart and trusty slide rule, which incidently never told you where to put the decimal point. Typical times for analysis were quoted (with some poetic license) as one day per data point. Even when the digital computer appeared on the scene the conversion of "raw" data to meaningful engineering quantities took a considerable time. Figure 10 is a summary of the method used to analyze offsite data at Boeing Vertol circa 1962. The process that then took 20 to 24 hours can now be accomplished in about a minute using sophisticated pre programmed analysis packages, telemetered aircraft data, or on board computing systems.

With modern data systems the technology and design engineers can choose any recorded parameter to monitor during specified maneuvers. He can use these to confirm the validity of each data point. In addition real time application programs provide the capability to manipulate data and present it in summary form which will be available for the engineer to review to make test condition or configuration decisions either during or at the end of the flight. If, during the testing, review of the data points show unexpected or uncharacteristic trends the condition can be reflown immediately. Within the constraints of fuel availability and test gross weight margins, a set of high confidence, high quality data can be developed on a single flight. If all the required data is not obtained on one flight (say when a center of gravity change is required to complete the data as would be the case in neutral point testing) the summary plot can be stored in the data base and recalled to add further data from subsequent testing.

It is realized that 100 percent of the necessary analysis cannot be accomplished on the flight test data system. When problems require detailed investigation and the expertise of an experienced specialist, the data will be made available, from the flight test data base directly to the engineer's desk, where a more detailed analysis can be conducted.

There are many aspects of fixed wing and rotary wing testing that lend themselves nicely to real time analysis. For example the standard elevator effectiveness, neutral point, level flight performance and maneuver boundary tests to name a few. The analyses presented in figures 11, a, b, & c, are now going to be accomplished by computer in real time in place of two or three engineers establishing manual routines for an analysis that often takes days. It is outside the scope of this paper to describe all of these routines in detail, however a brief description of three from different technology disciplines will provide an insight into the savings offered by real time analysis.

APPLICATION	CURRENT CAPABILITY	ATLAS CAPABILITY
Stress Analysis	-32 parameter capability -Steady/alternating loads/endurance limits	-Up to 150 parameter capability-more sophisticated analysis
Harmonic Analysis	-20 parameter capability -Resultants/phases for 3 harmonics for each parameter	-Up to 100 parameter capability. Ride quality index added
Spectral Analysis	-Fast Fourier Transform of 10 parameters. Output is normalized frequency & amplitude.	-Increased number of parameters. Cumulative spectral analysis for mission work will be added.
Air/Ground Resonance	-Analysis of 2 critical resonances. % damping of critical resonant frequencies.	-Increase number of critical parameters.
Flying Qualities	-Static & Dynamic Stability analyses for helicopter. -24 parameter time histories. -Elevator effectiveness. -Spec. comparison capability.	-Classical fixed wing analyses added including neutral point, Fs/g.
Performance	-Helicopter level flight, climb and hover performance (free and tethered)	-Capability extended to include fixed wing & tilt-rotor unique analyses -Download, Figure of Merit -C_L & C_D derivation -Maneuver boundaries.
Height Velocity	-Derivation of heights and velocities for safe recovery from engine failures	-Same program-but increased emphasis on simulation to flight test comparisons.
Airspeed Calibration	-Spatial positioning program using Del-Norte Equipment High speed calibrations TBD.	-Same program for low speed airspeed calibrations
Maneuver Loads	None	-Realtime derivation of bending moments for critical surfaces, eg. empennage, comparison with predicted strength envelope on Mx, My plots
Limit Checking	-Displays six top priority programs which exceed predicted limits. Warns of others which are within pre-defined margin of limit.	-Similar capability-increase in number of parameters monitored.
Propulsion	None	-Engine torque meter calibrations.
	OFF-SITE CAPABILITY	
Icing Evaluations	-Comprehensive onboard analysis system for performance, handling qualities and stress analysis.	-Similar capability.
Ship Interface Testing	None	-Capability to derive aircraft/ship wind and deck motion envelopes in real time. Will tie in with ships anemometry.
	PERIPHERALS	
Strip Charts	-32 parameter capability.	-32 parameter capability.
Pre-Flight	-Corrections to small changes in sensitivity and zero position done automatically.	-Will remain approximately the same -Instrumentation legend now loaded interactively.

Table 6. Comparison of Current and Future Real Time Application Programs.

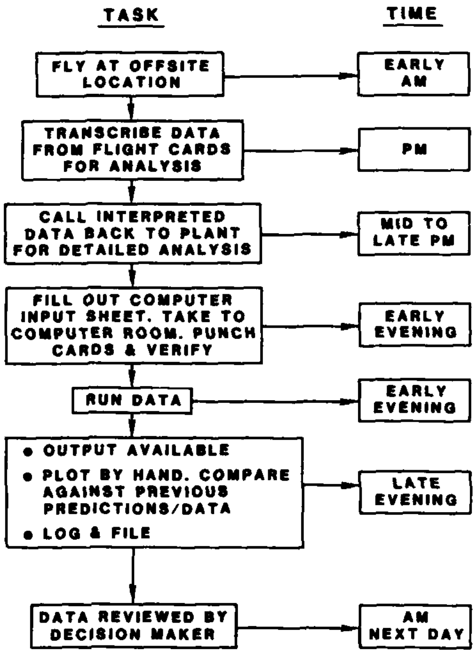


Figure 10. Data Processing circa 1962.

THE IMPACT OF DATA SYSTEM CAPABILITY ON FATIGUE LIFE CALCULATIONS

Manufacturers have historically been tardy in completing the fatigue life calculation process, in some cases taking up to two years after completion of flight testing.

Computerization has improved the situation to where the current systems are expected to turn the fatigue lives out in a few weeks. At the Boeing company 15 years ago, data processing was slow and produced voluminous fatigue life tabulations. Plots were prepared manually or by whatever computing facility was available at somewhat faster speeds. Life calculations were manually selected from tabulations and plots and loads were then cycle counted manually when local levels that exceed 100% of endurance limit were found. The process was simple enough, but very time consuming.

As a first improvement a computerized process was developed to interogate the data that exceeded pre-defined limits, and automatically extracted the S-N histogram to calculate damage and cycles to failure. This program was used to calculate the fatigue loads for the CH-47FRB helicopter. However fatigue damage rates still had to be manually transposed to appropriate elements of the fatigue spectrum. With this approach, documented fatigue lives were submitted to the customer about five months after the last flight. This was accomplished by hiring an "army" of technicians for the time required to calculate fatigue lives.

For the CH-47D helicopter the process was automated further. Three computer files were set up that contained mission profile informatior, a "loadset" file that assigned data samples to the appropriate mission profile and also an S-N curve file that described damage characteristics for each parameter. The major job was the manual preparation time required for file set up. The time required to provide the customer with the data was reduced to three months.

For the V-22 program, we will use a program that eliminates the need for manual transposition to the mission spectra and we will have the capability to display 'running' damage fraction for critical components at the termination of each test flight. The data system will also produce report quality data within one month of test completion.

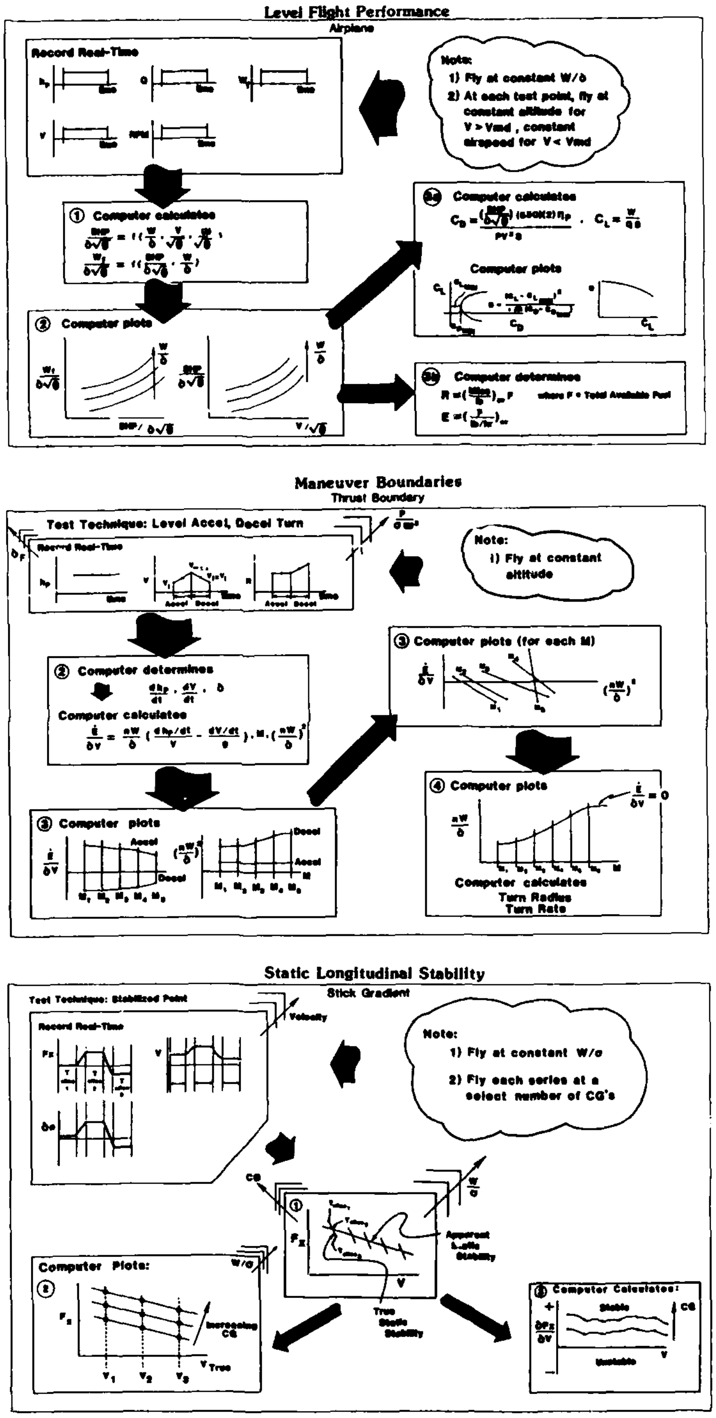


Figure 11 a, b & c. *Application Program Examples.*

HEIGHT VELOCITY TESTING

Height Velocity or "Dead Man's Curve" testing of helicopters has historically been an area of high risk. There have been very few helicopters which have completed this type of qualification testing without an accident of some kind. The purpose of this testing is to define heights and velocities for safe recovery of a single engine helicopter after an engine failure, or from which a fly-away can be successfully accomplished in dual engine helicopters.

The Bell-Boeing approach to H-V testing for the V-22 will be to use a combination of iterative simulation predictions and flight test. This will allow us to reduce risk to both flight crew and aircraft and to considerably reduce the amount of flight testing required to define the avoid areas. The method is not new, however the current computer capability significantly enhances it.

The test technique involves the following steps:

Unpiloted predictions on handling qualities techniques until a satisfactory time history is developed.

Piloted simulation to determine whether the off line technique is acceptable, followed by adjustments where necessary to establish a pilotable technique to a safe landing.

The definition of a predicted H-V diagram for comparison with flight test data, initially at a lower risk condition.

As flight test progresses the simulation math model will be updated and the whole process repeated until a reliable simulation of the flight test time histories is achieved.

This simulation technique was used on the YUH-61A program. However the time history comparisons were made "after the fact". On the V-22 program it will be possible to present predictions to the test team in real time and to compare time histories and critical parameters as the test is conducted. This will allow small adjustments in piloting technique and "go-no go" decisions to be made in real time, reducing or eliminating the need for post flight analysis.

SHIP/AIRCRAFT DYNAMIC INTERFACE TESTING

Ship/Aircraft Dynamic Interface data are, by necessity, recorded as quickly as possible as ship availability is invariably at a premium. The test team is normally on board for two or three weeks at the most, so the limited time available has to be used efficiently. The team also has to hope that the weather cooperates. When winds and sea states that meet the specification requirements do occur, it is imperative to obtain as much quality data as possible AND to be assured that the wind conditions that you think you are flying in are confirmed by the data. Unfortunately, the data is not reviewed in sufficient detail on board ship due to the need to use all available time to gather it. The data is, by necessity, reviewed over a period of months after the test has been completed. On the V-22 dynamic interface tests we do not have the luxury of an extended analysis period and will be recording and analyzing data in real time. We will merge ship and aircraft data in an attempt to produce wind envelopes as the data is flown. Although this will not completely negate the need for post test analysis, it will significantly reduce the need and will also ensure that all the test data required for wind envelope definition is obtained while the weather conditions are available. Figure 12 summaries the proposed methods.

SPECIFICATION COMPLIANCE TESTING

Specification compliance testing often requires extensive post flight data processing and analysis. For the V-22 program overlays of the specification requirements will be displayed on the maneuver summary plot in real time and will provide a quick reference to help ensure that the required data is obtained during the flight. In this way testing efficiency is improved by reducing the number of requirements to REFLY.

SAVINGS IN THE AREA OF INSTRUMENTATION PREPARATION

On the current BVC data system it is necessary for the instrumentation Engineer to build a handwritten "legend" for each test aircraft. This legend contains all of the working information that the data system needs to transform raw electrical signals into engineering units.

Currently, the way that this information gets into the system is via hand punched computer cards. This whole process will now be conducted interactively on the ATLAS data system.

The new approach provides a significant savings in preparation time and reduces the manpower required in the processing group. This is shown in Table 7 which compares manpower requirements for the old and new data systems.

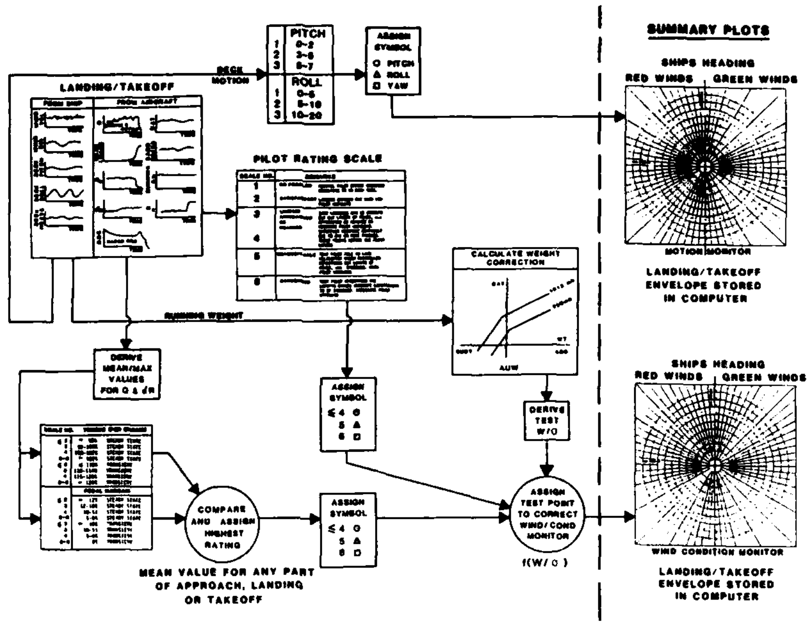


Figure 12. Proposed Shipboard Testing Flowchart.

JOB	PERSONNEL	
	OLD	NEW
FRONT END TECHNICIAN (TAPE LOADING etc.)	3	3
COMPUTER OPERATOR	2	0
FLIGHT TEST DATA TECHNICIAN	6	4
TOTAL	11	7

Table 7. Manpower Savings with the New ATLAS Data System.

CONCLUDING REMARKS

In summary this paper has examined factors which contribute to the reduction in the cost of flight testing such as the use of modern simulation capabilities and in particular the improvements which can be made in data processing, analysis and assimilation.

At the Boeing Vertol Company the gains achieved from real time data analysis have been greatest in term of increased value of data, enhanced data quality and an increased productivity as measured by productive flight rate.

To obtain maximum benefits from a sophisticated system such as ATLAS will, however, require careful and well thought out planning, a high degree of discipline to "stick to the rules" and enormous cooperation between team members. The use of such a system will be beneficial in that it will necessitate a close working relationship between the flight test department and the design and technology groups which will increase the useable knowledge of engineers in all areas. In the case of the V-22 program it will also foster a close working relationship between the two contractors and between the contractors and the government test agency. It is not easy to change the way one has done business for many years and reach a compromise on the most efficient way to conduct

testing or to do analytical tasks. On this program, these agreements are being made well in advance of first flight.

The other elements that support the program such as flight clearances, test equipment, etc., must complement the expedited assimilation of data. For example, at Boeing, as we developed our real time analysis capability, we found that our flight rate was being constrained by our ability to reballast the aircraft -- so we designed and built a rapid load-unload cargo handling system. The ever increasing number of data parameters that we have been able to fit into the data stream have given us headaches with pre-flight calibrations -- so we have fully automated that process and with the constant quest for improvements in the aircraft maintenance procedures, we will be able to improve our average of meeting early morning take off times, because the number of flights flown in a given day is driven by the takeoff time of the first flight of the day.

As our ability to assimilate data rapidly and to make go-no go decisions quickly improves, we are in danger of being constrained by the requirements of routine maintenance. We would like to believe that the development of production (or prototype) condition monitoring or on-board diagnostics will reach a stage where they can replace the current expensive inspection programs.

In other words, aircraft reliability, not data acquisition and processing may limit our productive flight rate in the future, and improvements in this area must accompany the improvements discussed in this paper.

ACKNOWLEDGEMENT

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USE OF DEMONSTRATION/VALIDATION PROTOTYPES: IMPACT ON TOTAL DEVELOPMENT COSTS AND TIMES

by

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SUMMARY

The development of a new type of military aircraft involves technical risks and uncertainties that are the greater the more advanced are the design solutions adopted.
The recourse to a pre-development program envisaging the fabrication of demonstration/validation prototypes before proceeding to the full scale development phase is a known possibility, and a solution that was and is adopted both in the USA and in Europe.
The results obtained by use of the demonstration/validation prototypes have been, in some instances, the subject of thorough analyses, which have confirmed the validity and convenience of these prototypes to the end of reducing the overall time span of the acquisition cycle and its costs, especially when the development was marked by significant technological advances.
In this study, an attempt has been made to identify the conditions that should determine the convenience and success of a pre-development program, and there are reexamined the advantages and disadvantages that the resort to such a program may entail in the present market situation and in a European industrial context.

1. INTRODUCTION

The primary objective of a development activity aiming at innovating a product is substantially to generate "information".
This bulk of information must be validated by an adequate evaluation and testing activity and be such as to permit the launch of the production of a qualified product which fully meets the needs of the market or the requirements of a particular Customer.
The innovation of a product, or even the development of an entirely new product, generally arises to satisfy the operational needs of the future.
The demand for innovation may be justified by the need to develop products that match new operational concepts, or are based on the exploitation of the latest scientific advances or technological progresses, or furthermore, that envisage the adoption of brand-new sub-systems and operational equipments.
From a merely technical viewpoint, the development process of an high technology product such as a military aircraft consists of activities performed according to a highly iterative cycle, including:
studies, design, estimates; testing; examination of results and their correlation with the estimates; refinement of computing tools; adoption of improved design solutions (macro-optimization); detail development of the executive design (micro-optimization), and eventually demonstration of actual system conformance to the requirements defined at its inception.
Typical testing tools are aerodynamic models, rigs of aircraft sub-systems, structural parts and assemblies, breadboards of electronic units and, when necessary, prototype aircraft.

2. PECULIAR PHASES OF A DEVELOPMENT PROGRAM

As known, from the viewpoint of the program, the whole development activity is generally divided into three main phases. They are the conceptual phase, the validation phase and the full scale development phase.
The objective of the conceptual phase is to define and select the systems concepts which warrant further development. The conceptual phase includes a preliminary design the outputs of which are adequately defined and technically feasible alternative configurations with the preferred configuration identified.
During the validation phase, the main program characteristics (system performance, development and production costs and relevant schedule) are validated and refined through analysis and design, hardware development or, even prototype testing and demonstration.
The full scale development phase entails a detailed design of the complete weapon system and also the fabrication of pre-production prototypes, to be used for a complete test and evaluation campaign.
This phase generally comprises all the activities carried out for product industrialization as well.

3. WHAT IS A PROTOTYPE?

Any industrial product that must reach the production stage, requires that its performance be verified and a "set up" be carried out by use of a few pre-production units or "prototypes". When referring to the acquisition process of military aircraft, the term "prototype" is generally given three meanings:

a) Research prototype. This is an aircraft designed and manufactured to explore fully innovative technical solutions and operational concepts, irrespective of the possibility or convenience to derive therefrom an industrial product of proven operational effectiveness at short term. There belong to this category experimental prototypes like the X-15, Fairey Delta, X-29, etc.

b) Demonstration/validation prototype. This is an experimental aircraft just a few units of which are manufactured, that are largely representative of the operational aircraft which is possibly to come. The demonstration/validation prototypes are used for technical and operational evaluations, but this does not necessarily involve that the Customer has taken the positive decision to go on to full scale development, and thence to production.
A prototype of this kind will be representative of the future aircraft essentially as to the significant innovations that can be embodied in the aircraft basic features (aerodynamics, structure, propulsion, flight controls and their integration, etc.).
The advance development of demonstration/validation prototypes is therefore justified when they are deeply innovated in those basic characteristics which, once firm, cannot be modified throughout the aircraft operational life, unless quite burdensome efforts are undertaken.
Conversely, the demonstration/validation prototypes will not be representative of those features and will be not equipped with those systems which, due to their own nature, do not require a tight integration with the basic systems and which can be changed to meet the special requirements of the Customer during the aircraft service life.

c) Pre-production prototype. An aircraft which is a strictly representative of the production aircraft, and which is used to validate in detail the final characteristics of the product and to get to the aircraft type certification. In some instances, when the aircraft basic characteristics are scarcely innovative, the pre-production prototypes can be replaced by the first production aircraft, which are utilized for experimental purposes, and thus for the demonstration of conformance (certification), prior to the delivery to the Customer to enter service.

In this study, we will essentially refer to the demonstration/validation prototypes to point b); our aim being to assess when and why the recourse to prototypes of this kind may be deemed useful to limit the overall duration of, and the costs to incur for, the development of a new type of military aircraft.

4. CONDITIONS JUSTIFYING THE USE OF DEMONSTRATION/VALIDATION PROTOTYPES

The advantages and disadvantages deriving from the use of the demonstration/validation prototypes in the course of the process of acquisition of military aircraft have been the subject of several studies; see Ref.s 1, 2, 3, 4.
On the basis of the above studies, and of considerations resting on the experience of the author of this paper, it results that the conditions that justify a resort to demonstration/validation prototypes should be the following:

1. Unavailability of previous experimental results inherent in very innovative design solutions that have been conceived on the basis of theoretical calculations and considerations and which affect the aircraft basic characteristics (structure, aerodynamics and basic systems).
2. Tight interdependence between the above basic characteristics.
3. Possibility of establishing a hierarchy among problems:
   a) by separating and confining solution of the design problems that concern the aircraft basic characteristics and involve a significant technological risk to the demonstration/validation prototype phase;
   b) by assigning the full scale development phase the definition of all other complementary systems that do not include serious uncertainties and definition/development risks; or by assigning again the full scale development phase the definition of those systems which, although engendering incertitudes or risks, are not actually so tighly intervowen with the basic aircraft configuration or systems.

5. ADVANTAGES THAT CAN BE OBTAINED FROM A PRE-DEVELOPMENT PROGRAM

The conditions that justify the use of demonstration/validation prototypes having been established, what are the advantages that can be expected?
Most literature on this subject stresses the proven possibility of attaining a greater efficiency throughout the development process.
We in fact know by experience that difficulties unavoidably arise during the development of a new product, and that a few design solutions as they were conceived, may prove unsatisfactory in the real case, even if a tough analysis effort had been devoted to them. It will therefore be necessary to take corrective actions, which should be fairly radical in a few cases.
According to the supporters of the pre-development programs, the fact to be able to operate on a very small number of prototypes dedicated to the definition and refinement of the aircraft basic characteristics, affords the advantage of permitting the adoption of timely and deep-going corrective actions, when required, without any worry to interfere with the parallel development of the other complementary systems (the development of which is conveniently postponed).
The embodiment of even extensive modifications in the demonstration/validation prototypes appears to be possible, and can generally take place at acceptable costs and in a reasonable time span because these prototypes are representative of the end product (viz. the operational aircraft) only in its basic features, and therefore the burdens deriving from the parallel development of complementary systems do not affect them.

Conversely, in a full scale development, all the technical requirements that come up at the same time must be forcedly taken into account. It will thus be necessary to consider both the structural and aerodynamic configuration requirements and the installation and performance requirements of all systems and sub-systems that make up the aircraft and on which its full operational capability is conditional. As a consequence, the full scale development phase of the aircraft, cannot but be the subject of a by far much more detailed planning that entails the development of plenty of diversified but highly interdependent activities.
The inevitable result is that the embodiment of significant modifications involving changes in the aircraft basic features, if required, would have a remarkable impact on both development costs and times.
Therefore, a scrupolous and detailed planning applied to a development activity that must all be performed at the same time is undoubtely useful to obtain a realiable forecast of costs and times, but, from a purely technical viewpoint, certainly represents a significant obstacle to the removal of defects and optimization of the product in the cases in which there exists the need to face highly innovative design solutions.
In the case of the development of new products that include very innovative characteristics, the adoption of demonstration/validation prototypes should therefore permit the actual total costs and times to be cut down. In fact, although it is not easy to define exactly when each type of aircraft reaches its real operational effectiveness, most authors agree in acknowledging that generally the defects that still emerge during the operational use are on the average less numerous and less serious in the aircraft that have been subjected to a pre-development before the Full Scale Development, than those found in aircraft that have not undergone a pre-development.
On the other hand, the recourse to a pre-development program, that is to the fabrication of demonstration/validation prototypes in the course of the validation phase, does not generally entail any increase in the duration of this phase that can be ascribed to the adoption of the prototypes, in comparison with a development of the validation phase based only on theoretical studies and experimentation on the ground. This is clearly apparent from the study mentioned in Ref. 2. This study evidences that the time taken by the development of the military aircraft acquisition programs has been constantly increasing in the last 30 years. The study also points out that this increase in the program duration has mainly affected the conceptual and definition phases (as a consequence of the much greater complexity of the weapon systems subject of the development), and that the programs which availed of demonstration/validation prototypes have not brought about increases in the validation phase duration with respect to the average values experienced.
The recourse to a pre-development gives other significant advantages. They concern: the decisional process, the involvement of the Customer and the use of competition.
As far as the decisional process is concerned, it must be observed that the development of a new military aircraft entails, in addition to a series of "micro-decisions" of technical nature which have been mentioned above, also a limited number of "macro-decisions" which condition the program progress and which are usually taken when the most significant events of the program occur.
In particular, the use of demonstration/validation prototypes affords the advantage of permitting a much more accurate estimate of the subsequent F.S.D. and production costs, than the estimates which can be made by availing of a definition and validation process based only on theoretical studies and experimentation on the ground just on models and part of the hardware.
The study to Ref. 3, indicates a percent increase in costs equal to 17% of the estimated value in the case of aircraft developed through demonstration/validation prototypes, and a percent increase of 35% of the estimated values in the case of aircraft for which a direct full scale development has been adopted.
On the other hand, the costs that should be incurred when recourse is made to demonstration/validation prototypes in an "austere" development, should be in the order of 10 to 20% and should not exceed 30% of the total full scale development costs.
In the case of the LWF program (YF-16, YF-17), Ref. 3 specifies that, in spite of the decision to proceed to a parallel development, that is a development by two different competing Contractors, the total cost of the pre-development phase incurred by the Customer did not exceed 18% of the total cost of the subsequent full scale development phase (F.S.D. having then been assigned to a single Contractor).
The actual cost of the pre-development phase should in reality be further compensated by the benefits in terms of lower costs, that can be imputed to the lighter impact of the modifications that should proceed to be necessary during the full scale development and production phases.
This lesser impact of the modifications is in turn ascribable to a higher refinement level of the aircraft as to its basic configuration and systems.
A demonstration/validation prototype program also offers the possibility of promoting a competition among several Contractors both on the initiative of the Customer (as more frequently happens in the USA), and as a result of independent initiatives (as more often happens outside the USA).
The greatest disadvantage of a competition is obviously that only one of the competitors is destined to win; at any rate it must be recognized that a condition of competition represents an exceptional drive for the realization of a highly cost-effective product.
In any case, the availability of an even very limited number of prototypes, representative of the final aircraft essential performance, at the end of the pre-development phase, will permit an effective marketing campaign to be launched. It will also be, as already pointed out, an essential reference for the definitive and

accurate estimate of the performance of the end product and the evaluation of the development and production times and costs.
In addition to this, the availability of the prototypes representative of the end product performance, cannot but favor the Activities (Contractor and/or Customer) that have taken the initiative to proceed to a pre-development, in case the need arises to seek new partners to accomplish full scale development and production.
The last characteristic of a demonstration/validation prototype program is the concrete possibility of limiting the subsequent commitments of the Customer.
Thanks also to the moderate financial and program commitments that are involved in a prototype program, the Customer is left with the actual possibility of not carrying out the subsequent full scale development and production phases, if the results of the pre-development do not justify this move.
As has already been stated above, the cost of a pre-development program can actually be a fraction of the total cost of the full scale development, and thus be a very small percentage of the total acquisition cost of a military aircraft.
Conversely, the timely proceeding to the validation of a new operational concept or to the testing of prototypes representative of new possible products that include significant technological advances, may enable an Air Force to reach a condition of advantage that may also be quite remarkable, if it is confirmed that the foreseen performance is attained. All the above, as detailed, at a reduced cost and with limited program commitments.
In the case the results of pre-development program should not justify the immediate "go ahead" for the full scale development, they might still prove useful at a later time to satisfy new needs that arise.

6. PROTOTYPES AND PROGRAMS JOINTLY DEVELOPED BY SEVERAL PARTNER COMPANIES

The development programs of military aircraft that envisage the participation of more than one Company, afford well known advantages, some of which are mentioned hereafter:

a) Sharing of the significant workload brought about by the complete development of a new military aircraft among different Partner Companies.
Optimal utilization of the existing facilities and resources.
b) As far as international programs are concerned, sharing of the program non-recurring costs among several Nations
c) Standardization of military materiel, operational methodologies and training criteria among allied Air Forces.
Improvement of the "interoperability" of military equipment.
More extensive standardization of parts and equipments.
d) Enhancement and larger diffusion of technological knowledges and production methods in industrial field, standardization of the production processes.

In the light of the above reasons, the recourse to cooperation programs among nations and partner companies nowadays an fact that cannot be renounced, in particular when very complex and advanced systems must be developed.
It ensues that, to realize a correct and balanced work sharing, it is necessary to realize a planning of the activities that is extremely detailed and acccurate. Unluckily these features are poorly compatible with the requirement, typical of the development phase, to proceed timely, and to take even radical actions, if required, to solve unforeseen problems or to remove situations that are in some way unsatisfactory.
How could a demonstration/validation program be implemented in a context of cooperation among several nations and partner companies activities?
The remedies that can be proposed, in the opinion of the writer, could be the following:

1. To provide for the assignment of the pre-development program to a very limited number of contractors (one or two). This would be justified also by the fact that the resources needed for a pre-development program are generally limited.
2. To have the largest possible number of activities developed by joint teams, in which there participate in a fully integrated manner, representatives of the Partner Companies. These teams should be given clearly identified objectives and follow positively defined and accepted methodologies.
3. Consequently, to divide among all Partner Companies only the full scale development and production activities, after the actual completion of the pre-development program (demonstration/validation prototypes).

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ENGINEERING MANAGEMENT FOR VALIDATION PROTOTYPE PHASE

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SUMMARY

The success and effectiveness of a concept demonstration-validation through the use of prototypes depend essentially upon the Contractor's engineering management activites, that are therefore to be carefully tailored to the goals of the program.
To this end, a special importance is borne by the activities for the definition of the most cost-effective prototype configuration, of planning, coordination and integration of the different specialty areas, of reduction and simplification of the formal qualification documentation and decisional processes.
These requirements impose that the Customer shapes the contract layout to flexibility criteria and that the Contractor adapts its organization by establishing an efficient task force led by a dedicated system engineering structure.
Essential factors for success are also a correct choice of the key people in the said organization structure and the completeness of the conceptual studies which represent the ground of a realistic planning of the prototype definition, development and evaluation activities.
The evaluation of the benefits obtainable in terms of complete development costs and time by using the suggested policies and techniques can be qualitative only, significant and homogeneous comparison data being scarce.
Another very important factor in reducing costs and time of innovative development projects, which is impossible to estimate from the quantitative viewpoint, is the opportunity of motivating the technical personnel and management by rewarding them with a tangible verification of their job in the shortest possible time.

1. DEMONSTRATION - VALIDATION PROTOTYPES

1.1 General and Main Characteristics

The experience gained in the USA and in Europe in the last few decades has confirmed that the advance development and testing of DEM-VAL prototypes permit program costs and risks to be reduced, and consequently a shortening of the development times to be obtained. It is in fact believed that the costs and time apparently added to the global acquisition program by the prototype validation phase, are more than compensated by the cost and time savings met in the subsequent full scale development. Besides, the afforded advantage is the greater the more the characteristics of the new product entail the need:

- to provide the Customer with the demonstration of validity of the innovative concept (operational and technological) included in the design;
- to generate information able to reduce the technological risks and increase efficiency during the F.S.D.;
- to reduce the commitment level of the Customer by starting long-term programs in advance, adhering to the most suitable program flexibility and control, and improving the quality of the decisions.

The prototypes destined for this purpose ("Y" prototypes according to the US designation), differ from both the "experimental" prototypes ("X" prototypes), which are rather used to acquire data and explore new technologies, and the pre-production prototypes used in the F.S.D. phase to qualify the project and its full producibility.
Project implementation and evaluation must thence become the subject of an industrial program that for the Contractor should be at the same time:

- austere, as the prototype development and fabrication costs should be maintained at a level just adequate for the above scopes;
- incentive-giving, as specific motives should be offered which replace the must to demonstrate the contractually specified performance.
  The incentive usually consists of the presence of a competitor (competitive fly-off), even if the ensuing higher costs can make marginal the economical advantage for the Customer that the DEM-VAL prototype phase generates throughout the acquisition cycle. Alternatively, it may consist of the need to satisfy the Customer's requirements for the launch of the F.S.D., and, as a result, for any follow-on business.

It can therefore be easily understood that all the above characteristics deeply affect both the Customer's and Contractor's program management criteria. The Customer must avail of "flexible" contracts, aiming at defining the general activity targets, instead of specifying the product, the procedures and the design and construction standards applicable. The Contractor must in turn adopt design and engineering management criteria that are optimized for the required austerity and flexibility.

1.2 Aermacchi's Experience

In the last 15 years Aermacchi has developed two different products (MB-339 and AM-X), which have proven useful to verify the validity of the DEM-VAL prototype phase concepts.

The development of the MB-339 has in fact entailed a low cost prototype phase, which has been covered by a special contract envisaging the fabrication of 2 validation prototypes. The evaluation of these prototypes by the Customer and the intensive flying by the Contractor have permitted the completion of the development and the definition of the production configuration (included in the same contract) in very short times and without the need for dedicated pre-production prototypes.

Obviously this approach has been possible because of the relatively low level of innovation and the derivative nature of the aircraft; but it resulted essential to the setting up of engineering management criteria based on flexibility and integration of the different disciplines, fabrication of prototypes and testing engineering included, through much centralized and agile coordination methods.

The AM-X development has on the other hand been characterized by a significantly different approach, conditioned by the international frame in which the program has been carried out, and by the ensuing need to agree beforehand upon the technical/operational characteristics of the end product, and upon the financial and industrial implications. For these reasons in fact, the definition-validation phase "on the paper" has immediately preceded the full scale development phase, during which the Partner Companies have manufactured 6 pre-production prototypes, which are presently being flown at the Companies' facilities.

This kind of choice has naturally imposed the adoption of quite different engineering management criteria, basing on much more formal procedures, on a fractionation and decentralization of more articulate functions and on more complex decisional processes.

Another meaningful experience made at Aermacchi, has been the development of the MB-339C aircraft, that is the version of the MB-339 installing advanced mission equipments (navigation and attack and self-protection systems), realized by the Company as a private venture by sticking to minimum risk and cost criteria (adherence to these criteria was also required of the sub-contractors charged with the development of the most important equipments), and postponing the full qualification activities to a subsequent industrialization/production phase.

To this end, there was thus produced a prototype the essential aims of which were demonstration and validation.

Although the experience acquired does not permit homogeneous quantitative evaluations and significant comparisons to be made, it has however been such as to highlight the necessity for/opportunity of adopting peculiar engineering management criteria in a DEM-VAL prototype phase.

2. ENGINEERING MANAGEMENT ROLE

DEM-VAL Prototype Phase: Structure and Main Tasks

The engineering and engineering management activities permeate the industrial commitment of the Contractor and the relationships between the Contractor and Customer throughout the DEM-VAL prototype phase.

These activities are the essential portion of the program cost and directly affect the remaining costs (Ref. fig. 1).

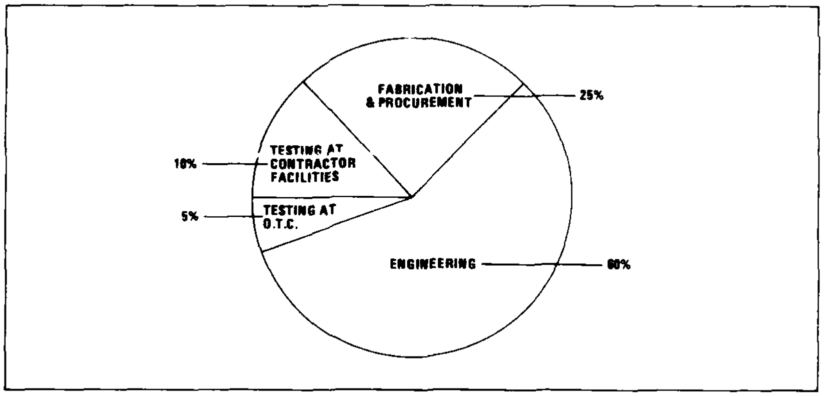

FIG. 1 - TYPICAL DEM-VAL PROTOTYPE PHASE COST BREAKDOWN

The main tasks of a "typical" DEM-VAL prototype phase include the transition activities from the conceptual phase to the full scale development phase, and are depicted in figure 2.

The following paragraphs therefore describe qualitatively the impact of the engineering management on the single main tasks, and the particular optimization criteria that can be suggested.

Additionally, it is assumed that the conceptual development phase has already been

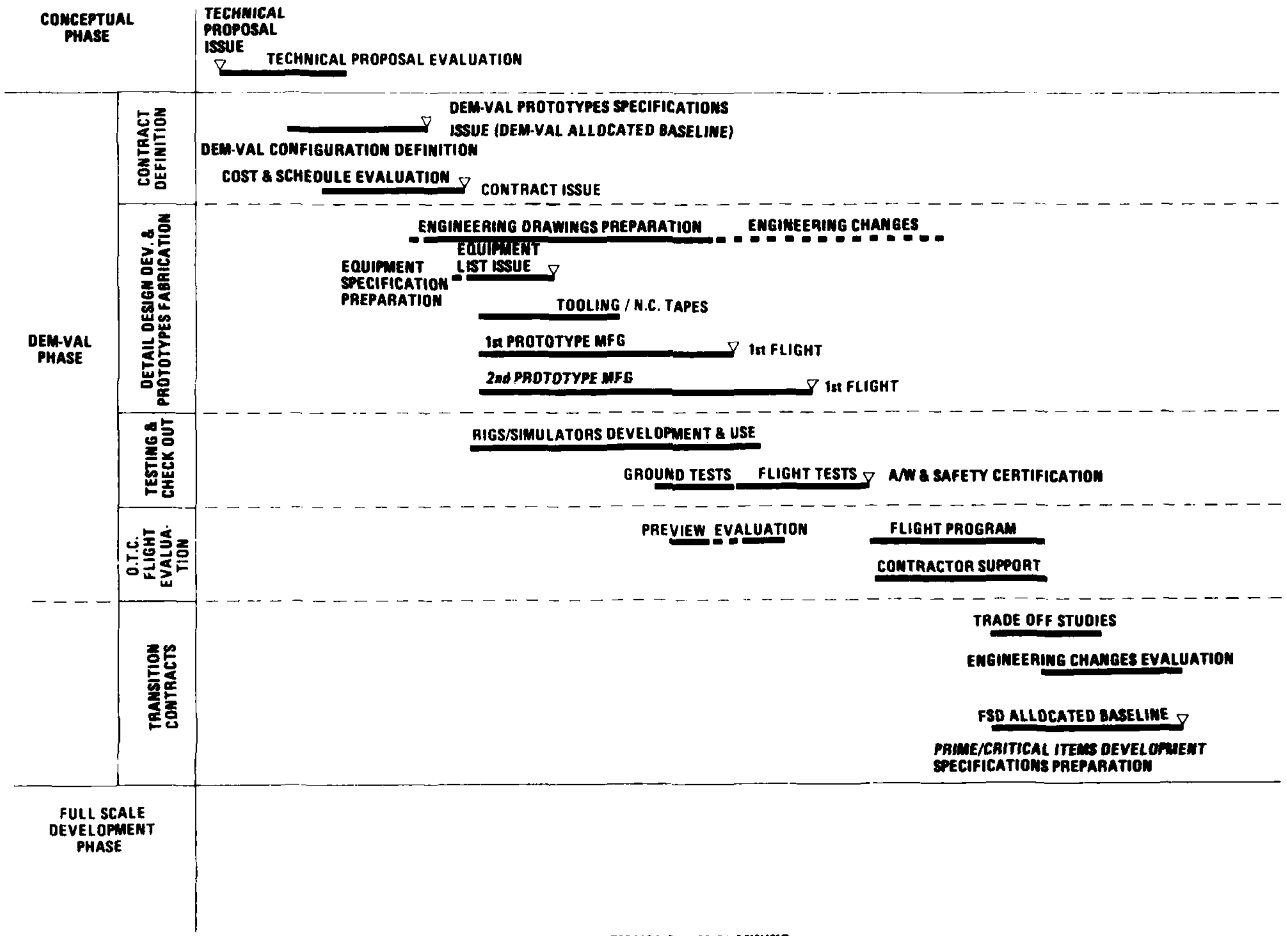

FIG. 2 - TYPICAL DEM-VAL PHASE PLANNING

accomplished through mission analysis, definition of the operational and maintenance concepts, and feasibility studies based on one or more preliminary aerodynamic projects; and thus that a functional baseline (through a system specification), and a technical proposal delineating the chosen solution, are available (refer to Appendix A for further details on the assumed conceptual study outputs).

2.1 Contract Definition
On the basis of the interest raised by the Technical Proposal, the Customer and the Contractor have to agree on the most effective contractual formulation of the activity subject of the DEM-VAL phase. Therefore, while the Customer should define the essential requirements that the prototypes must satisfy to permit an experimental validation of the operational concept, at the same time assuring the maximum flexibility of design and fabrication, the Contractor must develop a compatible prototype configuration and planning.
This process, that has a special importance in the success of the DEM-VAL program, must evolve in the presence of a tight cooperation between the Customer's technical staff and the Contractor's engineering management, and lead to the definition of the following:

a) Prototype Configuration
On the basis of the System Specification there should be identified the critical configuration items and areas that are of specific interest to the evaluation activity (e.g. airframe, engine, flight controls), and the applicable Preliminary Development Specifications should be prepared.
To produce these specifications the Contractor performs the functional analysis necessary to pass from the functional baseline to the allocated baseline; in order to reflect the design and test requirements applicable to the end product. Through a parallel functional analysis, these specifications may be conveniently "degraded" both as far as the completeness of the envisaged functions in their final configuration and their performance are concerned, so that the costs can be kept within the planned limits, though hitting the experimental evaluation targets.
During the above analysis it is therefore essential that the configuration areas be identified in which it is required that the prototypes be totally or partially representative of the end product.
The table in figure 3 gives a first approximation list of such configuration areas.

CONFIGURATION AREA	REQUIRED REPRESENTATIVENESS		
	TOTAL	PARTIAL	NONE
* VEHICLE SYSTEMS			
- Airframe aerodynamic/aeroelastic--inertial design	x		
- Airframe structural design		x	
- Propulsion system		x	
- Take-off/landing system	x		
- Flight control system	x		
* MISSION SYSTEMS			
- Communication/Navigation systems			x
- Attack systems		x	
- Escape systems			x
- Crew accommodation system	x		
- Miscellanea		x	
* LOGISTIC PROVISIONS			
- Maintenance	x		
- Standardization			x

Fig. 3 - DEM-VAL PROTOTYPE REPRESENTATIVENESS REQUIREMENTS

b) Test & Evaluation Criteria
The priority objectives of the DEM-VAL phase specified in the contract outline the test program in its different phases as follows:
GROUND TESTING:
The applicable program will be oriented exclusively to the purposes indicated hereafter:

- Safety
  Fatigue tests on parts or airframe segments will be aimed to verify the existence of safety margins adequate to a limited operational activity. Tests on rigs and ironbirds of systems critical for the safety of flight will have the purpose to verify the absence of undesired failure modes.
- Functional Check-out
  The functional check-outs will have the scope to highlight any malfunction that needs to be removed to ensure an effective accomplishment of the in-flight evaluation activities.
- Human factors
  The analyses of ergonomics regarding the cabin layout, simulation of flight conduct, and 1st/2nd level maintenance operations, as required for the refinement of the configuration being evaluated from the operational viewpoint, will be performed by using suitable mock-ups and flight simulators at the Contractor's facilities.

FLIGHT TESTING
The Contractor flight test program, will have the following main aims:
- to clear and expand the flight envelope;
- to preliminarily test the flying qualities;
- to test the basic airframe systems, the basic mission systems for safety/functions and the F.T.I. (Flight Test Instrumentation);
- to generate the data, procedures and use limitations required for the OTC (Official Test Center) utilization;
- to start data collection (deficiency reports, failure reports) for the required corrective actions.

The OTC Flight Evaluation will be essentially a mission-oriented testing, with the following purposes:
- to test the aircraft performance characteristics critical to the mission, i.e., the flying qualities, basic take-off/landing, climb, cruise, combat performance and weapon delivery, separation;
- to define, validate, refine the mission requirements/design specification for the end product;
- to collect data (deficiency reports, failure reports) for corrective actions and preliminary reliability assessment for the critical configuration items (engine, main equipments).

The test and evaluation activity might be carried on after the conclusion of the envisaged DEM-VAL program through possible transition contracts to the F.S.D. Phase (ref. para 2.5).

c) Cost & Schedule
The planning of the abovementioned activities (by means of the definition of a suitable WBS and SOW) at any rate permits an approximate evaluation of the envisaged commitment. The nature of the DEM-VAL program on the other hand makes difficult a precise appraisal of the Contractor's effort, and ineffective the application of penalties.
As stated in para 1 in fact, the Contractor shall be assigned non-contractual incentives to do his best in the shortest possible time.
The most used type of contract for this kind of programs is therefore the "fixed price" contract; the Contractor in turn will have to give opportune consideration to "design to cost" criteria, in order to avoid uncontrolled costs growth and reduce the industrial risks of the DEM-VAL programme.

d) Responsibilities
Although ensuring the flexibility necessary to guarantee the Customer a prompt action of logistic support, modification, experimental data processing and return, the contract clauses should identify, through precise "terms of reference", both the sharing of the responsibilites between Contractor and Evaluation Authority (O.T.C), and the integration criteria of their organizations for the flight evaluation program. In particular, to reduce the time taken by the evaluation and avoid duplications, it is advisable that the OTC accomplishes an evaluation preview, and that part of the flight test program at the Contractor's is carried out as Contractor Joint Trials. The evaluation program at the OTC will conversely be performed as Official Joint Trials (that is under the control of the OTC, but with the cooperation of the Contractor's personnel, who will give support for the FTI, logistics, test techniques and procedures, and data processing).

e) Documentation
A key factor for a successful, thus economical and rapid development of the DEM-VAL phase is the capability of minimizing the formal technical documentation requested in the contract, considering essential only:
- bimonthly progress reports on the development of the detail project, prototype fabrication and ground tests in order to enable the Customer to timely organize his evaluation PREVIEW;
- Synthetic design evidence and flight clearance prepared according to the Contractor's standards to clear the flight envelope;
- Collection of flight test reports covering the Contractor Flight Test Program;
- Preliminary Flight Manual including procedures, limitations, and data validated by the Contractor Flight Test Program;
- Preliminary Maintenance Manual/Inspection Manual covering the aircraft 1st and 2nd level maintenance only;
- Configuration identification documents based on Parts Listing and the schematic diagrams of the systems in the format used by the Contractor for the engineering drawings;
- Simplified engineering change procedures during the OTC flight evaluation phase, that are directly transmitted to and approved by the OTC (with pre-established budget limits);
- Processed data of the flight tests performed by the OTC;
- Data collection (deficiency reports, failure reports), and corrective action records;
- Evaluation of LCC using the information produced during the DEM-VAL phase.

2.2 Design Development and Prototype Fabrication
The preliminary development specification, "degraded" according to the criteria set forth in para 2.1.1a, and the associated S.O.W's are the inputs needed to lay down an accurate planning of design development and prototype fabrication. This planning will include all the activities required to make available concurrently and in the shortest possible time a fly-ready aircraft and the flight clearance covering the envisaged test envelope.
To this purpose, it is essential to ensure the maximum possible integration and overlapping of the following activities:

- Validation and definition of the aerodynamic project;
- Development of the structural project and the systems (through the definition of and agreement on the specifications of Vendors' equipments);
- Development of detail drafting;
- Development of the prototype fabrication activities;
- Development of the FTI design in accordance with the program requirements;
- Development of the Vendors' equipments at the Sub-contractors, to be checked-out at the Contractor's facilities by means of the special integration rigs;
- Development of the ground testing activities.

The most significant cost and time reductions can be obtained by adhering to specific design and fabrication criteria, such as:

- The adoption of very limited detail standardization, product segmentation and interchangeability requirements so as to minimize the production lead times and the cost of tooling (for instance by removing the need for master gages);
- The adoption of tools and processes suited to low quantity production (i.e. wooden dies), where innovative technologies are not involved, as for them the DEM-VAL phase requires specific evaluations;
- The postponement of value engineering to the production optimization phase (taking into account the fact that the most important value engineering choices must be made in the conceptual and prototype configuration definition phases);
- Qualification requirements applicable to the Vendors' equipments that consider only the fundamental aspects (safety, human engineering, concept demonstration, rather than reliability, accuracy, etc.). In this respect, the Sub-contractors should be motivated to provide the Contractor with their best performance by means of similar agreements;
- Adoption of *off-the-shelf* components *even if* not *optimized for the final* configuration, where functionally acceptable;
- Quality assurance and configuration management requirements capable of keeping at a minimum the formal evaluation procedures, and approval of engineering changes and waivers;
- Integration of the detail drafting activity with the prototype fabrication activity through:
  * the extensive use of CAD-CAM methods
  * the extensive use of stressed layout drawings in the fabrication organization, to accomplish the preliminary working processes at an early stage, while the development of the detail drawings will be concurrent with the manufacture of the parts
  * the adoption of the iterative cycle for a systematic validation of the drawings during the part fabrication and assembly phases. This solution will favor the release of the drawings to be validated as a function of the actual priorities, these priorities being difficult to plan individually
  * the integration of the F.T.I. (Flight Test Instrumentation) design and realization activities in the activities of prototype development and fabrication
  * Centralized coordination of the specialist resources (technologies and design engineering, testing engineering, experimental workshop, etc.), by establishing task forces and functional connections as specified in the following paragraph 2.3.

2.3 Flight Testing and Check-out for Airworthiness/Safety Certification

The engineering management should lead to the definition of the whole flight tests program throughout the general planning (ref. para 2.1) and design development (ref. para 2.2) stages.
More precisely, the design areas of the project that require an experimental evidence for the purposes of airworthiness/safety certification must be identified when the preliminary development specifications are prepared, while during the development of the detail project, such experimental verification requirements are to be unfolded both in terms of methods/techniques/test procedures and in terms of FTI to be integrated in the aircraft configuration as early as possible, in order to permit the testing engineering to timely plan the activities to its responsibility.
Eventually, during the flight tests, the concerned specialist areas should be present and provide assistance to allow maximum flexibility and effectiveness as well as prompt processing of data to be obtained, so that the entire flight envelope can be cleared immediately or the required corrective actions taken.
In view of the above, to optimize the in-flight experimentation program and reduce the times, it is of the utmost importance that effective coordination and liason be established among the different specialist areas and between them and the testing engineering. Coordination and liason will be based on the creation of well trained working groups led by the same system engineering management structure that has prepared the preliminary specifications and thus has the most general vision of and bears a long term responsibility for the program.
As mentioned in para 2.1d, an involvement of the OTC (preview evaluations, contractor joint trials, contractor trials observation) is envisaged to take place during the flight tests at the Contractor's. For its own evaluation and general coordination requirements, the OTC will refer to the Contractor's engineering management.

2.4 Flight Evaluation at the Official Test Center and Contractor Support

Also as far as the Official Joint Trials are concerned, it is necessary that the general evaluation criteria be identified, the test methods determined and the extent of the test program assessed as early as at the time of contract definition. All this will permit the Contractor's support effort to be planned in terms of specialist engineering and testing engineering required both at the OTC and at the Contractor's

facilities to assure a fast development of the tests, the generation of the requested data and any necessary change embodiment and logistic support.
The effectiveness of this sustaining activity depends essentially on the following factors:

- Direct interface between the Contractor's Engineering Management and OTC, by use of fast and simple formal communication means, such as:
  a) From OTC to Contractor
     * Deficiency Reports
     * Failure Reports
     * Query Notes (to request information and data)
     * Flight Test Instructions (to notify the test programs and the requirements for direct support by the Contractor's personnel)
     * Official Evaluation Reports
     * Occurrence Reports (to report events, situations of peculiar importance to the end of airworthiness);
  b) From Contractor to OTC
     * Flight Clearance Notes, to state that configurations are operable and to specify their limitations
     * Reply Notes (to forward the requested data/information)
     * Recommendations
     * Simplified ECP's (to propose configuration changes that can be embodied during the evaluation program);
  c) Meeting Notes
- Coordination continuity by the Contractor Engineering Management with respect to the specialist engineering that has developed the project, the prompt availability of which must at any rate be ensured for the sustaining activities that cannot be planned beforehand;
- Suitability of the logistic support and the maintainability characteristics for the evaluation purposes.

The maintenance concept being of extreme importance for a correct evaluation of the system, it is essential to establish the required representativeness of the prototypes with respect to the ILS-LSA preliminary plan. Because the optimization of the reliability of the single equipments is postponed to the F.S.D., it is important that the representativeness be ensured for the purposes of preventive maintenance rather than for those of corrective maintenance. In the same way, in view of the fact that evaluation is intensive and thus spans over a relatively short time, the representativeness of preventive maintenance will be opportunely limited to the 1st level.
The logistic support will therefore be mainly a responsibility of the Contractor, as far as the replacement of failed components, possible repairs and the embodiment of modifications are concerned. The presence of the specialist engineering will however be assured during these operations:

- to implement the data base necessary for the development of the subsequent LSA;
- to adopt the corrective actions that are required for a smooth continuation of the DEM-VAL program.

2.5 Flight Test Program and Contractor's Activities Subsequent to the F.S.D. Decision

The use of the prototype aircraft might be effectively extended <u>after</u> the decision to proceed to the Full Scale Development is taken, possibly by means of suitable transition contracts having the following aims:

- to evaluate trade-off & engineering changes developed to correct deficiencies or implement new requirements;
- early qualification of production equipment where available; (e.g. envisaged G.F.E. for the F.S.D. and production phases);
- operational/maintenance procedure definition on the basis of the performed experimental evaluations, and of the validation/definition of the mission requirements;
- R&M data collection and analysis for the development of the ILS-LSA plan;
- preparation of the development specifications covering the prime item and the critical items, the LCC studies and planning of the F.S.D. and production activities.

3 Engineering Management Plan

3.1 Technical Program Planning and Control

a) In the Contract Definition Phase, the Contractor's activities impose that a working group be established which includes key personnel of the system engineering areas dedicated to:
   - the preparation of the DEM-VAL configuration development specifications through the necessary functional analysis and allocation of requirements;
   - the development of the WBS and detail specifications tree;
   - the definition of the SOW's, planning and cost evaluations with sufficient detail to permit the selection and allocation of the resources in the frame of the Contractor's organization.

This working group will report to a responsible person appointed to the position of project coordinator throughout the DEM-VAL phase. In view of the nature of the main activities envisaged for this role, specific engineering management knowledges are obviously required.

b) After the Contract Definition, the needs for effective coordination and high flexibility deriving from the Contract Definition require the adoption of specific organization arrangements, the goals of which are:

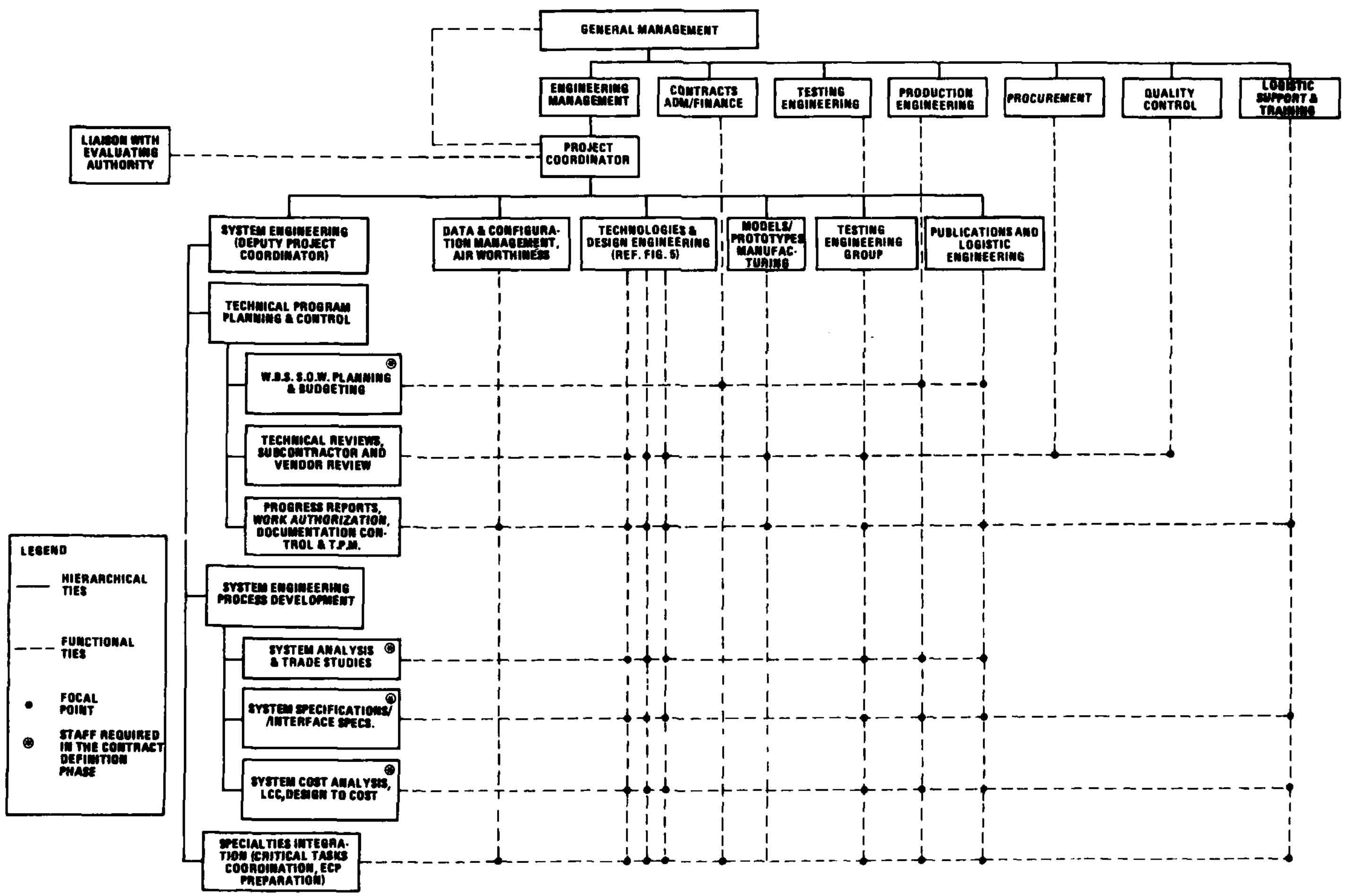

FIG. 4 - ENGINEERING MANAGEMENT, ORGANIZATION LAY OUT

- to minimize the length of the decisional processes, the uncertainties and the conflicts;
- to maximize the parallel cooperation of the various specialist areas and provide for their coordination.

For this purpose it is of the utmost importance that an organization structure be defined, which is characterized by functional and hierarchical ties capable of ensuring:

- the constant presence and the capability of taking prompt action of the person responsible for the project through the direct control of the dedicated system engineering resources, that will be increased with respect to the initial staff mentioned in point a) above;
- the availability of dedicated specialist resources at the different engineering areas that operate in tight connection with the abovementioned system engineering staff;
- the availability and support of the units of the different functional departments within the budgets that are concurred upon, according to the direct instructions given by the project coordinator.

The chart in figure 4 summarizes the hierarchical and functional ties of an organization featuring the abovementioned characteristics and ensuring in particular:

- the reduction of the command chain, by shortening the decisional processes, and concentrating many responsibilities in the hands of the project coordinator, whose choice has therefore a critical importance;
- the implementation of a very tight control on the system configuration, on costs and technical risks through a dedicated system engineering structure;
- the exerting of a very accurate technical coordination and program control on the specialist engineering activities through the same dedicated system engineering structure;
- the deep integration of the design detail development activities, prototype fabrication and experimental verification activities by unifying their functional dependency.

The chart in figure 4 also delineates the multiple functional ties among the different specialist areas and the requirements for "focal points", who are to be selected in the ambit of the system engineering structure, or in that of the specialist line as a function of the technical field of knowledge which is prevailingly required.
Eventually, as far as the organization of the specialist engineering resources (technological area and design engineering) is concerned, to the end of an optimal use of these resources, it is advisable that their functional relationships be attuned to the program WBS (which in turn should preferably conform to the system functional breakdown criteria), by setting up working groups or task forces composed of people coming from different specialist sectors. Key personnel having appropriate technical and managerial knowledges will lead these working groups and task forces.
An example of such an organization is shown in figure 5.

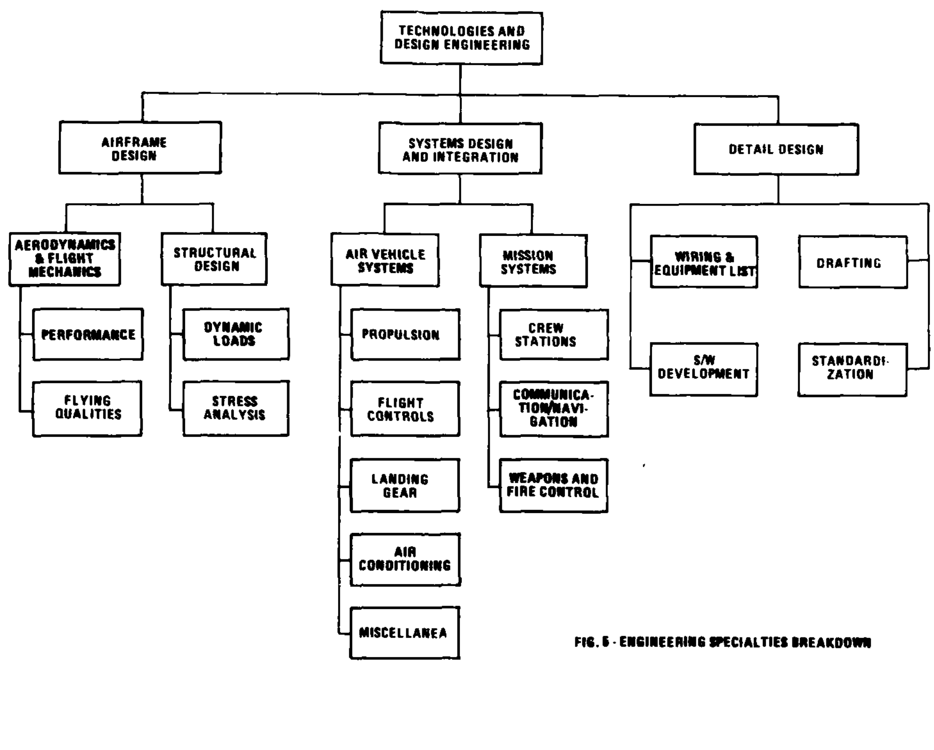

FIG. 5 - ENGINEERING SPECIALTIES BREAKDOWN

3.2. System Engineering Process

The system engineering process for the derivation of the prototype configuration, the necessary trade studies and the generation of the preliminary development specifications of the prime item and the critical items, will be performed by the system engineering activities indicated in figure 5, according to the criteria already set forth in the previous para 2 and with the support of the concerned specialist areas.

The functional analysis at the system breakdown levels corresponding to the sub-systems of concern of the specialist areas, up to the generation of the specifications covering the single subsystems and equipments will be carried out by the specialist areas; the connected coordination and the evaluation of trade-offs remain conversely a responsibility of the system engineering in order to ensure its homogeneity and to verify the design to cost objectives.

The above activity being not a subject of the contract of the DEM-VAL program, but only an activity of preparation and support to the definition/modification of the prototype configuration, will have to be traceable through in-house documentation with minimum standardization requirements.

3.3 Engineering Specialties Integration

The optimal integration of the specialties obviously depends on the organization/subdivision of these specialties according to the criteria indicated in paragraphs 2.1 and 2.2, on the timely availability of the resources and on the effectiveness of the information system adopted for the control and visibility of the program.

However, the nature of the project, and the characteristics of the DEM-VAL program require that special integration and coordination efforts be made, these efforts consisting in the establishment of small task forces, when the following circumstances occur:

- need to avoid postponement of activities located on the program critical path;
- need to remove uncertainties and conflicts in critical project areas;
- need for new planning and ECP preparation actions that entail an immediate and limited involvement of different specialties.

4. CONCLUSIONS

The advances that can be obtained in the field of the engineering management techniques can hardly be defined quantitatively because they depend on the ability to rationalize, and thus to foresee, the logical connections in the development processes and the mutual relationships among the various and increasingly complex aspects of the project.

In spite of the paramount contribution that automation has given to the everyday activities of the human society, this ability is still essentially bound to the personal experience and the inner and professional motivations driving technical personnel and managers, who are required to quickly adapt to the changes in the technological scenario and to the unavoidable unexpected events still aiming at the known objectives.

In view of the above, the DEM-VAL prototype phase, which sets concrete objectives that can be attained at a fairly early time, may represent a strong motivation factor, and thus an efficiency factor in engineering management.

APPENDIX A

CONCEPTUAL STUDIES OUTPUTS REQUIRED TO START THE "DEM-VAL" PHASE

The main objectives of the conceptual studies are related to:
- the definition of the basic system requirements (operational concept);
- the definition of the maintenance concept;
- the identification of a feasible configuration (feasibility analysis).

a) The definition of the Operation Concept includes:
   * mission requirements
   * operational life cycle
   * operational deployment/distribution, utilization requirements, effectiveness factors (Ao, MTBM, , COST EFFECTIVENESS, etc)
   * performance/physical parameter requirements, environmental requirements.

b) The definition of the maintenance concept includes:
   * level of maintenance, repair policies, maintenance responsibilities
   * supportability requirements (R&M, human factors)
   * ILS requirements, effectiveness factors, environmental requirements.

c) The feasibility analysis includes the studies for:
   * the identification of the possible alternatives
   * the relevant evaluation in terms of cost effectiveness and technical-economical risk
   * the selection of the preferred system configuration.

This activity is performed through the system engineering iterative process that can be summarized in table 1A.
The outputs shown in this table must permit the preparation of a TECHNICAL PROPOSAL that indicates:
- the chosen FUNCTIONAL BASELINE (by means of the system specification);
- the physical and operational characteristics (by means of a technical description and the results of the preliminary design);
- the cost and program evaluations (by means of the S.O.W of the different subsequent phases, the advanced procurement, test evaluation, production plans and the L.C.C. studies).

TASK (Ref. MIL--STD-499A)	CONTENT	OUTPUT
MISSION ANALYSIS	OPERATIONAL CONCEPT DEFINITION	BASIC SYSTEM REQUIREMENTS
FUNCTIONAL ANALYSIS	TRANSLATION OF THE BASIC SYSTEM REQUIREMENTS INTO FUNCTIONAL DESIGN (OPERATIONAL & MAINTENANCE FUNCTIONS)	TOP & HIGH LEVEL FUNCTIONAL FLOW DIAGRAMS
ALLOCATION	TRANSLATION OF FUNCTIONAL DESIGN INTO THE DESIGN REQUIREMENT ALLOCATION	REQUIREMENTS ALLOCATION SHEETS TIMELINE SHEETS
SYNTHESIS	TRANSLATION OF THE DESIGN REQUIREMENTS ALLOCATION INTO A PHYSICAL SYSTEM BREAKDOWN IN CONFIGURATION ITEMS AND RELEVANT FUNCTIONAL INTERFACES	HIGH LEVEL SCHEMATIC BLOCK DIAGRAM, PRELIMINARY LAYOUT DRAWINGS, PRELIMINARY DESIGN STUDIES (aerodynamic design included)
LOGISTIC ENGINEERING	MAINTENANCE CONCEPT DEFINITION	PERSONNEL/TRAINING/ DATA REQUIREMENTS, LOGISTIC SUPPORT ANALYSIS DOCUMENTATION
LIFE CYCLE COST ANALYSIS	ACQUISITION AND OWNERSHIP COST ESTIMATE THROUGH PARAMETRIC EVALUATION AND SPECIFIC ANALYSIS	DESIGN TO COST TARGETS, LOGISTIC SUPPORT ANALYSIS DOCUMENTATION
OPTIMIZATION	EVALUATION OF THE ALTERNATIVE SOLUTIONS IN TERMS OF: SYSTEM EFFECTIVENESS, COST EFFECTIVENESS AND LCC	TRADE STUDY REPORTS
PRODUCTION ENGINEERING	PRODUCIBILITY ANALYSIS CRITICAL REQUIREMENTS/ PROCESSES/MATERIALS IDENTIFICATION	TRADE-OFF STUDIES LCC IMPACT ADVANCE PRODUCTION PLANNING
GENERATION OF SPECIFICATION	FUNCTIONAL BASELINE DEFINITION	SYSTEM SPECIFICATION

TABLE 1A - SYSTEM ENGINEERING PROCESS FOR THE CONCEPTUAL STUDIES

SCHEDULE AND COST CONTROL OF DEVELOPMENT

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SUMMARY

The increase of cost expenditure and time consumption for the development of aircraft is a fact on most of the programmes performed in the past.

This paper will show different reasons for the increases and also presenting methods how to plan an aircraft development programme to avoid them.

Therefore the possibilities and in some cases their contrary extremes for programme execution in terms of adapted programme philosophy and management aspects are shown as well as the contractual and economical environment.

Furtheron the available tools for the planning and control of programme execution on the basis of decided programme philosophy are presented.

It is explained that in normal development programmes the increases in its majority results not from technical problems and/or risks, but they results from contractual, economical and management decisions which are fixed by customer and contractor before the beginning of a development programme.

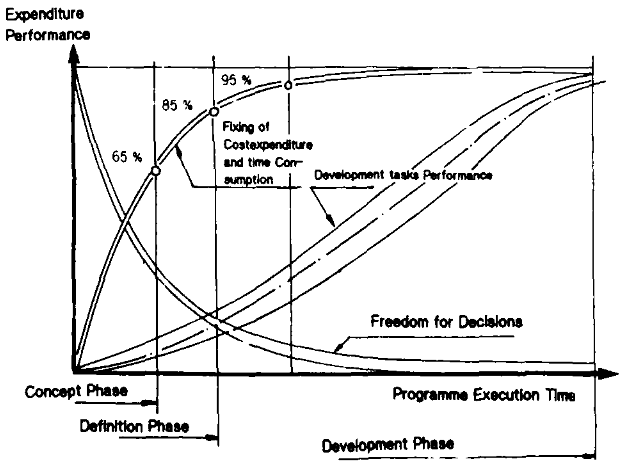
1. INTRODUCTION

A survey on past and present aircraft development programmes shows a permanent increase of necessary cost expenditure and lead time for the development of highly sophisticated aircrafts.

The reasons for this are various and differs from case to case but a few of them should be highlighted in the following; taking not into account the follow-on costs of e.g. in service phase of an aircraft system.

The basis of the money and time consumption will be established during the earliest phases of a programme (concept- and definition phase) namely with the decision how to perform a development programme and which programme philosophy will be used for the execution.

Schedule for Fixing Expenditure versus Freedom of Decisions



2. ALTERNATIVE ENVIRONMENTS FOR PROGRAMME EXECUTION

For possible programme execution and philosophies a few alternatives with major effect on development phase cost and time will be given.

Furtheron it must be stated, that also the premise to start a development phase e.g.

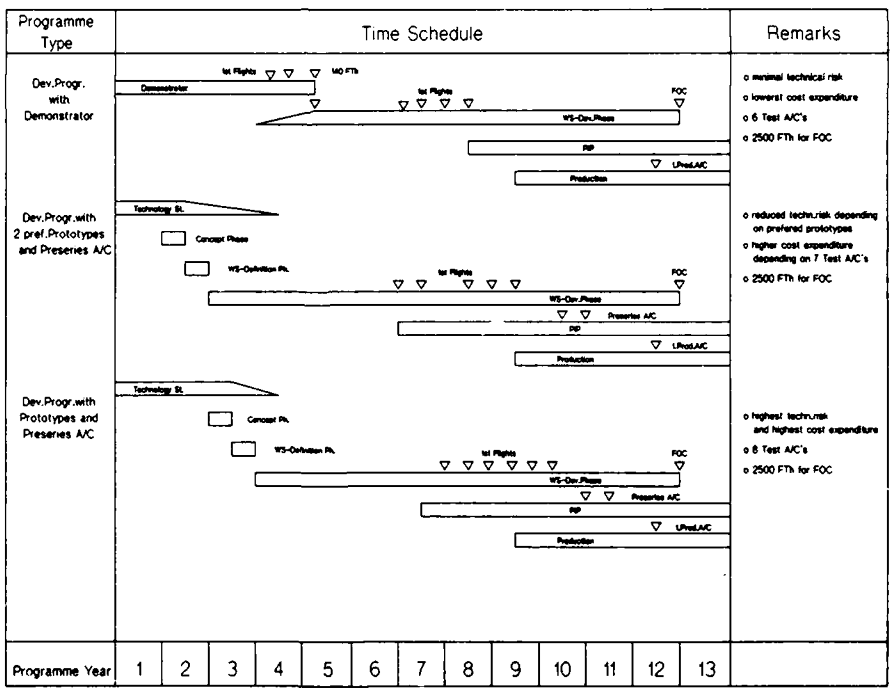
- Technical and operational requirements fixed
- Contractual obligations (customer/contractor) including used technical and management procedures must be agreed
- Organization (customer/contractor) and in case of multi partner programmes worksharing arrangements must be clear
- Configuration, system lay out and preliminary design established

must be fulfilled.

2.1 Programme Type

Basically for programme types can be stated that the kind of execution has direct influence on cost expenditure (whereby for these examples as shown below the FOC-date and the No. of FTh was assumed as identical).

Alternative Programme Types for Aircraft Development



2.1.1 Aircraft Development Programme with Demonstator (Pre-Prototype)

In this example the available new technologies and techniques will be combined and checked in the demonstrator.
The availability of approved technologies gives the highest benefit to the follow on development programme and reduce therefore the technical risks.

The customer furtheron can check at the earliest possible stage the operational benefits fo new technologies and modes.

2.1.2 Aircraft Development Programme with 2 Prefered Prototypes and 2 Pre-Series Aircraft

This programme reduces the technical risk depending on the early availability on preliminary flight test results from the 2 prefered prototypes, but it incorporates techniques and technologies not checked in their combinations and the resulting operational benefits.
Furtheron the risk for the production-investment-phase is reduced because the manufacturing experience of the prefered prototypes is already available.

2.1.3 Aircraft Development Programme with Prototypes and 2 Pre-Series Aircraft

This programme leads to the highest technical and cost risks depending on high overlapping of the programme phases and the latest availability of flight proved results for the production aircraft.

2.2 Programme Collaborations

The necessary budget availability at one customer, the availability in one country of all components required in an aircraft and the requested standardisation especially in military aircraft programmes leads in a collaborative programme execution on customer and therefore taking into account also political and economical aspects also on contractor side.

The following picture shows as an example for one partner the resulting cost expenditure benefit for collaborative programme execution.

Trade off between Programme Costs and Collaborativ Partners

Collaborativ Partner		1	1/4	1/2/3	1/2/4	1/2/3/4/5
Collaboration Factor	(%)	0	20	15	20	25
No. of Production Units		300	500	700	800	1000
Workshare Portion for Partner 1	(%)	100	50	40	33	30
Nat.Development Cost for Partner 1	(%)	38,2	22,9	17,6	15,3	14,3
Fly away Price for 300 Units ord.by Partner 1	(%)	61,8	57,3	54,4	53,4	51,5
Total Cost for Partner 1	(%)	100	80,2	72,0	68,7	65,8

Assumptions:
- Partner 1,2 and 3 already have performed Collaborativ Programmes, with the Partners 4 and 5 no Collaborativ Programmes was performed
- Learning curve = 90%
- No of Units/Partner 300/1 ; 300/2 ; 100/3 ; 200/4 ; 100/5

The above picture shows, that the total programme costs per national budget is lower as more partners develop and produce an aircraft.

But it has taken into account, that a national programme provides an achievement of the national requirements without any compromises and in case of export, independency from other partners or governments.

2.3 Programme Philosophy and Programme Content

The basic philosophy for execution especially on cooperative development programmes covers the following aspects, which has a direct influence on development budget and/or time consumption.

2.3.1 Management Aspects

Extremes of some management aspects are shown whereby the decision for each of the extremes can be significant

- Overall Aspects
  - One/multi programme languages
  - One common/different national laws
  - Performance of "indivisible" work in an "integrated team" of more partners/at one partner company
- Reporting System
  - Reporting level: high/low
  - Reporting period: 6 monthly/monthly or permanent
  - Reporting content: problem areas/description of all activities
  - Reporting type: overview computerised/detailed descriptions
- Way of Decision
  - Overall responsiblity/split responsibility
- Authorisation of Work
  - Periodical/permanent
  - High PSP level/low PSP level

2.3.2 Aspects of Programme Execution

The programme execution especially in the light of collaborative programmes bears e.g. the following alternatives:

- Engineering and Test Area
  - Single/multi flight test centre
  - Use/no use of hack aicrafts
- Manufacturing Area
  - Single source - /multi source manufacturing
  - Single source - /multi source final assembly
- Overall Programme
  - Check functions/no check functions on partner companies activities
  - Acceptance/no acceptance of partner companies certifications
  - Incorporation of all or only flight critical changes

2.3.3 Aspects on Programme Procedure

The procedures technical and management wise have direct impact on programme performance e.g.:

- Tight/overall configuration management procedure
- Common/uncommon standards
- Identical/different computer programmes for e.g. stress calculation
- Identical/different software languages
- Identical/different tooling concepts
- Identical/different manufacturing procedures
- Identical/different tech. pubs. procedures
- Identical/different test procedures

2.3.4 Aspect on Programme Organization

The possible programme organizations on customer and contractor side are various, so that only a few extremes can be given:

- Customer Organization
  - One leading nation/joint agency
  - Independent/dependent from national activities
  - Large/small organization

- Contractor Organization
  - External Organization

    The basis of the contractor organization should be in line with the type and structure of the customer organization

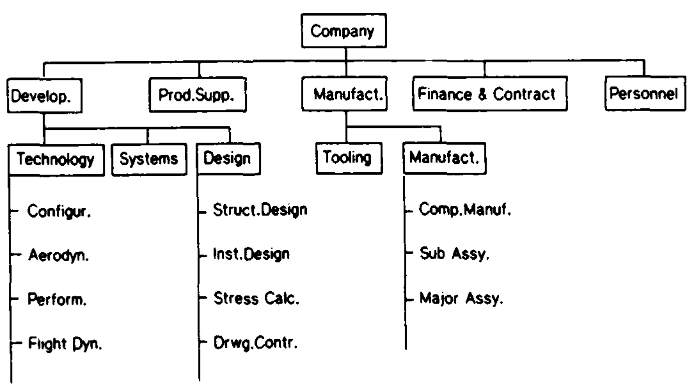
  - Internal Organization of Partner Company

    There are basically two types of internal organization in the light of the programme performance

    o Function Orientated Organization

    The programme activities will be performed in the function orientated organization of the company, whereas the programme manager is more or less a coordinator because the "how and when" of task performance is given by the responsible department leader

Function Orientated Organization



o Matrix Organization

A matri" organization for the performance of programme activities (whereby the specialists only for defined time/activities are engaged) is shown below.
This matrix organization has e.g. the following advantages/disadvantages:

- Advantages

  All activities can be headed in terms of "when" by the programme manager

  . The specialists are only for the period of task performance engaged to the project

  . One responsible for the overall programme and also for each programme function is identified

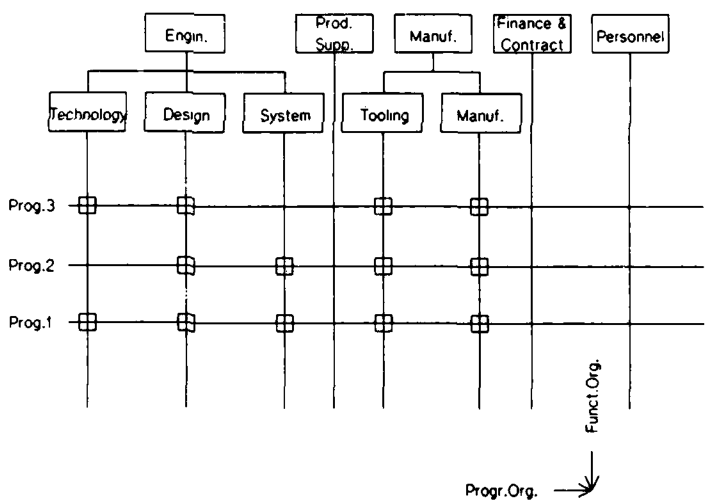
  . The ways of information are short

- Disadvantages

  . The specialist have partially multi-responsibilities

  . The capacity adjustment is more difficult

Matrix Organization



2.3.5 Programme Content

Depending on the requirements and on the technology level taking into account the long life time of an aircraft and therefore the expected alterations in the environment development, the alternative content of an aircraft system vary e.g.

- New Structure with

  new/existing engine

  new/modified/off the shelf equipment

- Incorporation of new/approved technology and techniques

- Lay out in terms of single - or multirole aircraft

3. MANAGEMENT METHOD AND MANAGEMENT TOOLS FOR PROGRAMME PLANNING AND PROGRAMME CONTROL

Independent on the programme alternatives in the case of the environment mentioned above, for the handling of a development programme management methods and tools partly EDP supported will be used for planning and controlling the overall development with the target of economic relations between cost expenditure and time.

The following gives an overview of used methods and tools.

3.1 Tools for Programme Planning

3.1.1 Project Structur Plan (PSP)

For the handling of the programme it is necessary to structure the programme whereby on facts such as

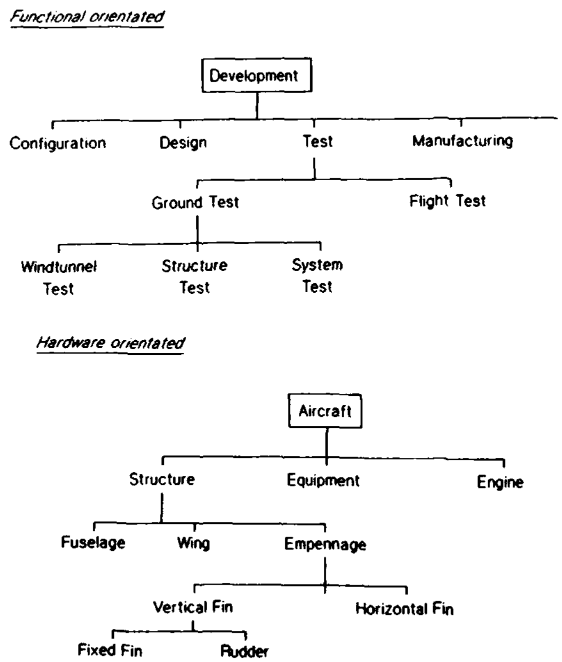
- Hardware orientated
- Function orientated and
- Organization orientated

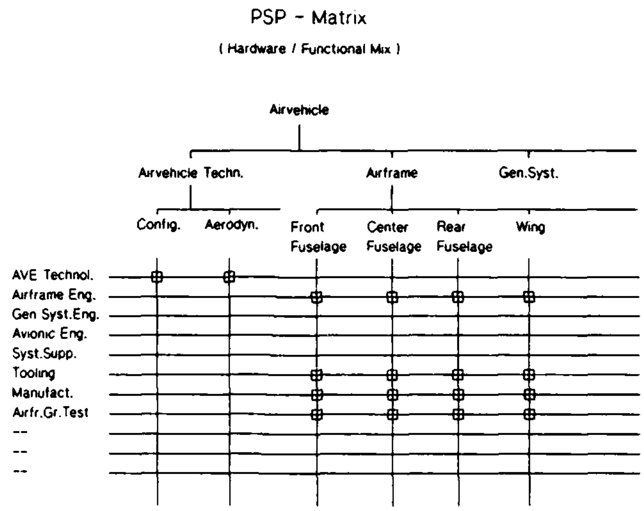
will be given attention as well as on

- Element size in terms of budget and
- Workshare

A good PSP can be used throughout all phases of a programme whereby the element content can be different from phase to phase.
A PSP used in the practice for programme planning and controlling is a mixture of hardware orientated and functionally orientated which can be presented in a matrix form.

Principles of Project Structure Plan (PSP)





3.1.2 Statement of Work (SOW)

For the development of an aircraft in accordance with the technical and operational requirements all necessary activities will be described in a SOW which should be structured in line with the PSP.

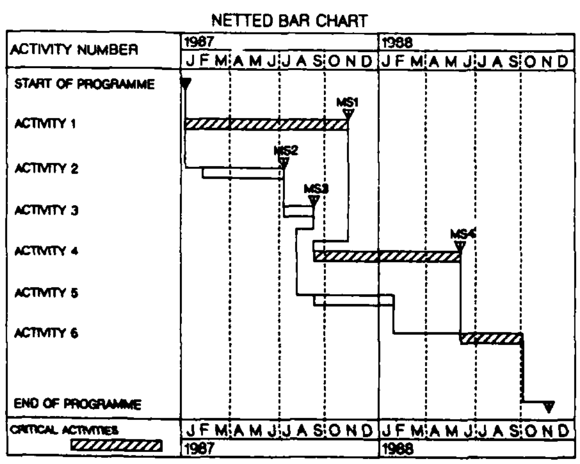
The SOW which will be used as an annex to the contract must reflect the content oı the different activities and because the activities tc be performed are in the future, all essential assumptions and exclusions must be included.

3.1.3 Time Schedule

In line with the PSP and based on the activities as described in the SOW time schedules for the overall development and all major activities will be established.

In the past basically bar-charts were used depending on the fact that detailed networks are too complex and gives no quick overview on results of single slippages.

A new method the "Netted Bar Charts" combine the critical path method of networks with the quick information on possible resulting facts for the total programme in accordance with the slip of a single event.



3.1.4 Cost Estimation

For the estimation of development cost different methods which of course also are dependent on the knowledge of the programme content e.g. SOW, programme philosophy, will be used.

3.1.4.1 Cost Models and/or Parametric Estimates

Parametric Estimation is being used with increasing effect. Parametric models generally necessitate a considerable amount of calibration to reflect the product development process in design and manufacturing.
Once calibrated, they produce very quick results which is particularly useful for trade offs between various design and manufacturing approaches.
Parametric models are being used to assess the cost estimates produced in the analytical manner, and to confirm the results with a second likewise reliable methodology.

3.1.4.2 Analytical Cost Estimation

Based on the PSP all activities for the programme execution will be detailed in such a manner that the planning specialist in collaboration with the specialist of the relevant activity can overview and estimate the activity in terms of manhour and non personnel cost over the total running time.

It has to be stated that the correctness of the cost estimation and the time schedule depends on the considered assumptions and exclusions and each change to them modify the overall programme development cost and time schedule.

A further essential aspect in line with programme cost are the contractual conditions such as

- Economic conditions
- Exchange rates especially in accordance with international programmes
- Regulations for customs, duties and fees
- Price policy in terms of fixed or reimbursement price
- Security requirements

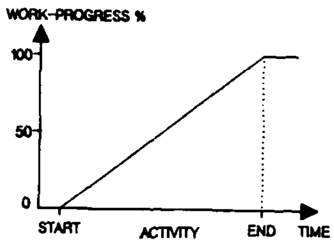
which normaly leads to an higher cost increase than all technical changes together.

3.2 Programme Monitoring Tools

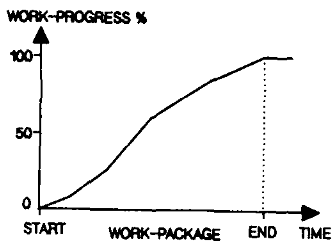
For the monitoring of the programme activities in line with the PSP, SOW, schedule and cost estimate, workpackages will be established which cover all detail information for the tasks to be performed by one discipline.
A workpackage with its linkages to other workpackages will be handled like a contract between the programme manager and the task performing departments.

As measurement a percentage system of "workprogress" giving a relationship between technical task performance, time consumption and cost expenditure. Therefore all tasks in one workpackage will be weighted on its technical content which than can be correlated to expenditure and time schedule.
The system itself gives the possibility to sum up to each level of programme structure.

WORK-PROGRESS



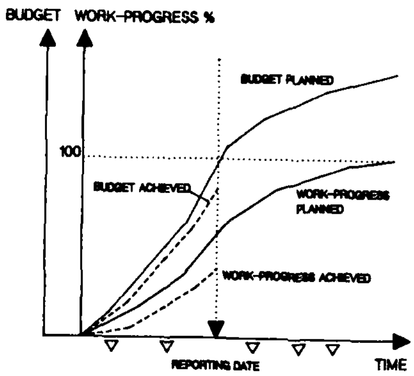
- COMPLETED ACTIVITY :
  WORK-PROGRESS = 100 %
- LINEARISING OF WORK-PROGRESS OVER THE TIME



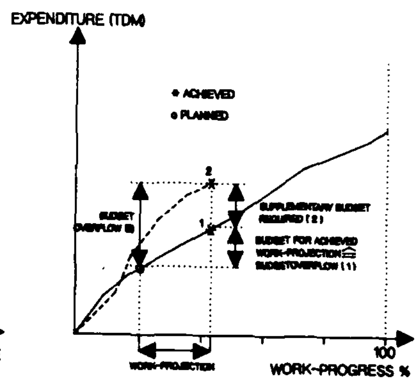
- WORK-PROGRESS OF WORK-PACKAGE => OVERLIE OF THE WORK-PROGRESS FROM THE ACTIVITIES
- COMPLETED WORK-PACKAGE
  WORK-PROGRESS = 100 %

WORK-PROGRESS

COMPARISON PLANNED/ACHIEVED
WORK-PROGRESS,BUDGET,MILESTONES



EXPENDITURE/WORK-PROGRESS
DIAGRAM



The planning data are stored in a data-base, sorted in line with the PSP whereas the actual data for manhours and non personnel costs (important is to use the obligation for non personnel costs) will be automatically correlated via the PSP-numbering system and made available by book-keeping departments.

For the technical progress of the activities the milestone achievement or the estimated percentage of task achievement will be used and compared with the planned workprogress.
This method with its relative comparison of planned and achieved workprogress in connection with the knowledge of the critical path presented in the netted bar-charts gives for the programme manager a relative picture of the programme status indicating e.g.

- Target reached in time (earlier/later) within the planned (higher/lower) cost expenditure

The workpackage planning also will be used to check the availability (non availability) of the required personnel and non personnel capacities during the relevant time.
In case of non availability in time a rearrangement between different programmes must be performed, or if this is not possible subcontracts must be placed and/or timely limited additional manpower must be contracted.

3.3 Programme Control and Reporting

The information available to the programme management on different levels of the PSP will be used to control the aircraft development in terms of:

- Technical achievement

- Cost expenditure

- Time consumption

The method of operation for the programme manager to control the programme is dependent on the circumstances of the plan deviations. The corrective actions must be performed immediately after the knowledge of the deviation and the result will be monitored by the next programme check, which may internally be done in a one month step.

The internal reporting necessary for placing corrective actions must be performed on a more detailed basis and in a shorter time interval as the external reporting which for cost saving reasons only should include information on cost expenditure (not for fix price contracts), time schedule and technical achievement like:

- Reporting item in line with planning
  (on agreed base of e.g. 5% deviation)

In case of higher deviations and/or occuring technical problems influencing the requirements of the product a detailed problem-area report explaining recovery action must be given to the customer.

4. RESUME

The availability of EDP supported planning and monitoring tools as well as cost estimations on model base (which often only will be used for checking and correlation purposes) and analytical methods including risk assessments gives the possibility to keep the target in a good relationship between

- Cost effectiveness
- Time effectiveness
- Satisfactory fulfillment of technical and operational requirements

But as we all know, the increase of

- Cost Expenditure and
- Time Consumption

is a fact on most development programmes of sophisticated aircrafts.

This mainly depends with a share often more as 50% on cost and/or time increase on reasons outside the technical area and can be listed for customer, contractor and both sides as follows:

- Customer Related Facts
  - Overloading of the product in terms of technical, logistical, operational requirements
  - Multi role aircraft instead of single role aircraft with fall out performance for further roles
  - Extreme high administrative requirements for reporting on very low levels (the management teams of customer/contractor should be balanced)
  - Cost increase by incorporation of late costed exclusions
  - Change of economic conditions, exchange rates and customs/duties/fees (depending on large development phase time span)
  - Inconsistency in time schedules between GFE deliveries and aircraft development programme or slippage of GFE deliveries (e.g. engines)

- Contractor Related Facts
  - Over specifying of equipments/components of the aircraft
  - Usage of too advanced or too sophisticated or unchecked computer programmes (usage of computer programmes generate sometimes additional cost and not cost savings, but normally the quality of the technical or administrational results increase whether it is necessary or not)
  - Fragmentation and/or duplication of work as a result of workshare arrangements and/or unclear/multiple responsibilities

- Facts Related to Customer and Contractor
  - Long time to reach decisions, especially in multi-national programmes with equal sharing between the partners
  - Incorporation of additional requirements and/or modifications/alterations in terms of "Nice to Have"
  - Incorrect use or mixing up of cost terms e.g. fly away price $\longrightarrow$ system price
  - No optimal lay out of time schedule (overlap or follow on) for programme execution

If we try to keep down cost expenditure and time consumption on development of aircraft we have to watch the cost and schedule drivers which in most cases are contractual/management decision items and not technical items.

These contractual/management items must mainly be clarified before development phase starts.

Nevertheless also the technical related cost driving activities especially

- The extreme usage of computers
- The over specification of the product and resulting in
- The continous incorporation of changes (not necessary for the performance of the product or not effective during development phase) must be stopped.

Only a combined and disciplined procedure in the restriction to the necessity on technical and commercial requirements can avoid for aircraft development programmes a further increase on cost expenditure and time consumption and giving us additional budgets for new research and development programmes.

PEOPLE, PROCEDURES, PERFORMANCE: THE KEYS TO IMPROVING THE DEVELOPMENT ENVIRONMENT

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SUMMARY

A growing management issue over the past 20 years in the United States Aerospace and Defense industry is the ever-increasing percentage of total product labor cost attributable to the professional work force. Therefore, the challenge of improving the performance and productivity of these workers, especially in a development environment, is now and will remain a most critical element in a firm's overall profitability.

This paper begins with an overview of white collar productivity: its growing importance in the Aerospace and Defense industry, its resistance to the more traditional approaches to productivity improvement, and the challenges facing managers who try to attack it. The author explodes some of the popular myths surrounding the issue, and then sets forth a model to help managers understand and thus control the elements comprising white collar productivity. The paper then recounts a case study in which this model was used with great success by a major aerospace manufacturer. The paper concludes with a list of techniques for successful implementation of white collar productivity improvement programs.

INTRODUCTION

> For the rest of this century, and far into the next one, the competitive battle will be won or lost by white collar productivity. -- Peter Drucker

The cold, hard facts of economic survival are pointing to a new candidate for enhancing competitiveness and profitability in the United States: white collar productivity. For many, this is indeed a fresh concept, as management attention for decades was focused on building a strong manufacturing capability. Efforts were centered on the blue collar worker and a "fair day's work for a fair day's pay." Industrial Engineers led the way with innovative ideas on division of labor and task time standards.

Today, this is no longer the case. The search is on across numerous industries, including Aerospace and Defense, for fresh ideas and techniques to reduce the cost and increase the value added of the white collar work force. Why is this sector receiving such attention, and why are the answers so elusive to management? Here are the principal reasons:

-- **The white collar sector is exploding**. In the United States, white collar workers now substantially outnumber blue collar workers. This is especially true for the Aerospace and Defense industry. Figure 1 illustrates this trend with published data from a major defense contractor. As you can see, by 1990, it is projected that "non-touch" labor will represent 75 percent of the total production man-hours.

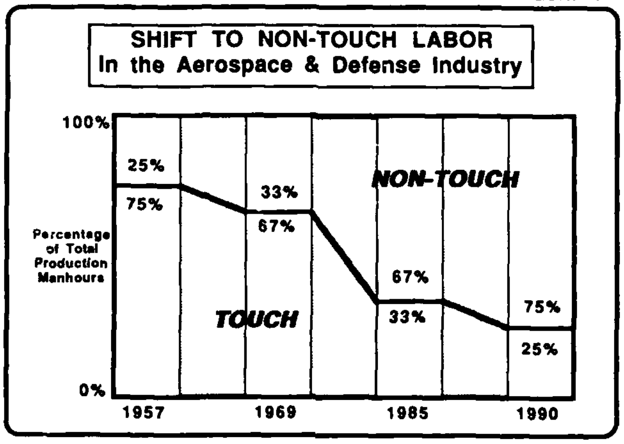
-- **The potential for white collar productivity improvement is significant**. With other natural resources, we are more and more aware of waste, and have become very careful to avoid it. But our performance must be rated far less than satisfactory in managing the white collar work force. Recent studies have estimated white collar productivity at only 40 to 60 percent of its potential. As one Aerospace vice president recently interviewed summed it up, "Automation and other tools have limits, but the ability to enhance human achievement is boundless."

-- **Blue collar improvements have been marginally exhausted**. We've beaten our production workers to the point where further "improvement program" efforts affect ever-smaller groups of workers and produce even smaller benefits. As one senior executive put it, "Improving blue collar productivity is a rear-guard action. We cannot hope to compete against the vast supply of low-wage blue collar workers in the developing countries through blue collar productivity, no matter how much we improve it."

-- **Traditional perspectives and approaches to productivity improvement don't work**. White collar work is different from blue collar work. The old notions of time standards, scientific management, and division of labor don't translate well to the white collar arena. It is simply unrealistic to paint blue collar methods white and expect them to pay off. They don't. In the good old days, it was easy: throw in some capital, add the latest technology, measure it closely, and productivity improvements are guaranteed. Those days are gone.

-- **White collar improvement techniques that are wildly successful in one company many times fail miserably in another.** White collar performance is too complex and qualitative to respond to a "hammer in search of a nail" approach. Too often, we expect the latest software or popular management technique to provide solutions to all our productivity problems. My experience has taught me that it doesn't work that way. The issues may be similar among companies, but workable solutions must match unique needs and be sensitive to specific cultures.

FIGURE 1



We don't need to convince ourselves any further that the benefits from white-collar improvements can be significant. What we do need, however, is a clarification of the issues, a description of the tools available, and an outline of the process that takes this potential from a concept to a real payoff. It is my hope that this paper will shed light on each of these vital topics. The returns are there and they're worth pursuing. But first, let me provide some brief background on the research basis for this paper.

RESEARCH BASE

Most of the information and viewpoints used in developing and refining my hypothesis for this paper comes from the world's best teacher -- direct experience. However, in an effort to supplement the data base from my own background, an original research study was undertaken in two phases. The first phase was conducted late last year with the help of an independent research company, and consisted of delivering around 300 self-administered questionnaires to upper level management personnel in the Aerospace and Defense industry. Each recipient was asked to ensure that the questionnaire was completed by that person in the firm most knowledgeable about and most active in productivity programs.

The degree of interest in this project was gratifying. Despite the holiday season, approximately 20 percent of the questionnaires were completed and returned. Of these, 50 were received in time for inclusion in the tabulation and compilation of results. The response demonstrated the professionalism of the sample, being thoughtfully detailed and rich in information. For their assistance, I wish to acknowledge the help and input of these professionals in companies throughout the United States who participated in this undertaking.

The second phase of the research was equally exciting. During this time, personal interviews were conducted with senior Aerospace and Defense executives across the country. The purpose in each interview was to understand better, from the executive's perspective, such issues as:

-- The future direction of the company, and the expectations for productivity in meeting these objectives.

-- The role of the senior executive in encouraging productivity improvement efforts throughout the organization.

-- The keys to improving productivity within the company based on experience.

Each of these leaders was most generous with his time and insights. For this, I express my sincere appreciation.

Now, I'd like to go deeper into the concept of white collar productivity. The best way to do this is to dispel some widely held myths about it.

WHITE COLLAR MYTHS

White collar productivity, for all its potential, seems to defy our understanding and frustrate our efforts. Much of this can be laid to the myths surrounding this topic. There are at least four major ones.

Myth 1: Everyone knows what productivity is and why it is important.

Without a doubt, this is the first myth that must be dispelled. Today, "productivity" is one of the most often cited but least understood concepts in the business vocabulary. This is especially true with regard to the white collar work force. As mentioned, white collar work is different from blue collar. It involves different people, different skills, and different motivations, as well as difficult-to-measure outputs, less rigid procedures, and more sensitive cultures.

Because of these differences, simple definitions of productivity that focus on straightforward measurement of direct inputs and outputs based on work standards are inadequate for properly managing white collar workers. Let me offer a practical, alternative definition:

> White collar productivity is a <u>relative</u> measure over a <u>specified time period</u> of the <u>total value</u> of the <u>results</u> provided to an organization through the <u>collective</u> efforts of a group of white collar workers in relationship to the <u>cost</u> of operating the group.

Under this definition, white collar productivity improvements can be shown as long as meaningful results can be attributed to the group's efforts and the group's cost of operation can be identified. The important point is that white collar productivity is not working harder individually but working smarter collectively.

Myth 2: Everyone wants to improve productivity.

Improving productivity, especially in white collar areas, is a concept receiving a great deal of attention in the United States today. To deny its importance, at least in theory, would be considered almost unpatriotic. Yet we know that white collar productivity improvements have been disappointing over the past twenty years. Why? One big reason is lack of true management commitment. In the questionnaire results, the factor cited as playing the most significant role in the failure of previous productivity improvement efforts was <u>insufficient management support and involvement</u>.

The first step to improving white collar productivity begins with top management. There must be a full endorsement from these key individuals, with their continued active and visible support throughout the process. Their tacit approval of funds for such efforts is not enough. Managers must become "change agents" to help overcome resistance to change, and their expectations for demonstrated results must be constructively transmitted throughout the organization.

Myth 3: Automation is the answer to improving productivity.

Computers: as wonderful as they are and as ubiquitous as they are becoming, it's too simplistic to assume that computer automation will somehow magically cure performance ills. Automated inefficiency is still inefficiency.

The Hughes Aircraft study on R&D Productivity, published several years ago, discussed three elements more critical than automation in their influence on professional work performance:

- -- Caliber of employees
- -- Work environment
- -- Effectiveness of supervision

This study pointed us in the right direction. Today, however, based upon my experience in dealing with the performance issues of the white collar work force, I believe the list of critical elements is somewhat different:

- -- Focus
- -- Organization
- -- Motivation
- -- Process
- -- Management Effectiveness

As an alternative to the previous research, these five elements are being presented here somewhat out of turn. However, keep them in mind, as I'll be returning to them shortly when I present a much more structured concept of white collar productivity.

Myth 4: Professional productivity improvements can't be measured.

"No one knows how to measure productivity" is one of the most widely heard comments from managers of white collar personnel. Yet, I suspect that this statement often is more an excuse for not proceeding than the raising of a issue to be resolved in the early stages of designing a program.

There is no argument that sophisticated performance measurement systems, such as those used in many blue collar areas, are simply not appropriate for white collar environments. But this does not erase the fact that simple measurement systems can be developed which are more than adequate. Four important realities regarding measurement to keep in mind:

-- The system should be group-specific, based upon close alignment with the group's "outputs" or "services"

-- Relative, not absolute, performance improvements are the most important to measure

-- The value of the measurement must not exceed its cost -- in other words, keep it relatively simple

-- The measurement itself must not defeat the purpose of the entire program -- use the measurement as a means to encourage improvement, not as a club to force it

Let us now turn from myths about white collar productivity to methods for dealing with the reality.

THE NEED FOR A MODEL

There are literally hundreds of valid techniques that can be used to address individual white collar performance issues. However, well-intentioned "solutions" may be misdirected and targeted on symptoms rather than sources of problems, or worse, may be a solution in search of a problem. And, of course, nothing works unless it takes into account the interaction of the activity of managing and the object of management. The complexity of this problem demands a holistic approach. This is where most individuals turn to models.

I believe Robert D. Gilbreath, in his recently published book Forward Thinking, best describes the need for models:

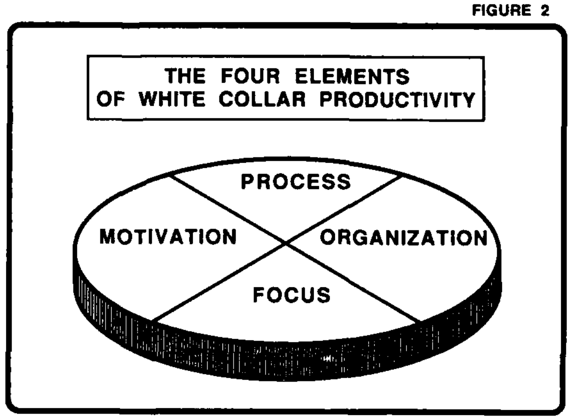
> We constantly create not only mental but physical models of our business conditions, using them to understand what is going on in reality and to test (simulate) management actions upon reality. In their most general sense, models represent the way we look at and operate in our changing world. Examples of business models range from the basic, such as budget scheduling reports, organization charts, and position descriptions, to fairly sophisticated ones including strategic plans, on-line inventories, and interactive simulation programs.

The point to be made is that a model for developing a better understanding of all the elements influencing white collar productivity can be proposed. Such a model needs to be sensitive to the special nature of the white collar environment. It must also help put individual management techniques into perspective and must help us isolate symptoms of poor productivity and trace them to their sources. Based upon experiences within the United States Aerospace and Defense industry, I believe such a model has been developed. I would now like to share with you the model itself and, then, some direct experience and results from applying it within the Aerospace and Defense industry.

A MODEL THAT FITS: THE ELEMENTS

This model slices the total white collar experience into four elements, as shown in Figure 2. They are **Focus**, **Organization**, **Process**, and **Motivation**.

FIGURE 2



As simple as this breakdown is to depict and visualize, it is nevertheless extremely revealing and powerful to those who use it. Virtually every environmental, social, organizational, or technological constraint, tool, or management issue can be related to one or more of its primary elements. We begin by asking the key questions listed below:

WHITE COLLAR PRODUCTIVITY

ELEMENTS

Focus	**Are we doing the right thing?**
Organization	**Are we best structured and integrated?**
Process	**Are we doing things right?**
Motivation	**Do we want to do our best?**

Focus: Are we doing the right thing?

One senior Aerospace executive made it clear in a recent interview, "My job is to provide a clear understanding to all employees of the company's strategic direction. Strategic direction should not be left for others to translate."

The linkage between strategy and the activities of the professional work force is called **Focus**. This is where performance improvement must begin, with clear direction and clear vision throughout the organization. Explaining why his aerospace company had an extremely motivated work force, one executive said, "[Our] people are results-oriented, with shared business goals. Extraordinary effort is expended to obtain this desired result."

Focus helps define whether detailed work activities add to (focus upon) performance as defined by the company's overall operations strategy. Specifically, the issues addressed in an evaluation of Focus include:

-- **Role definition**. Is the mission of the department clearly stated and understood? Are the functions supporting that mission effectively defined for all personnel? Which of these functions are the most critical to achieving our objectives?

-- **Required outputs**. What are the outputs necessary to meet departmental objectives? Are these unnecessary outputs that contribute little or nothing in terms of value added? Are there missing outputs that detract from overall performance?

-- **Performance goals**. Are performance goals effectively defined at all levels? Will meeting these goals ensure that company objectives are met?

-- **Value added by activity**. What is the value added of each activity relative to a desired output? Do redundant activities exist? How can low-value-added activities be modified or eliminated?

-- **Overall resource allocation**. Are proper levels of resources provided to meet department objectives? Are the appropriate labor skills present within these resources? Is this allocation appropriate when future business objectives are considered?

Organization: Are we best structured and integrated?

Organization refers to the infrastructure through which the efforts of the professional work forces are coordinated, communicated, and controlled. Several of the aerospace executives spoken to during the research phase of this paper believed Organization to be the most critical of the four elements. As one of these executives put it, "Organization is the key. Minimize the layers of management and push down the responsibility for managing. That's what it takes." However, it's amazing how many companies operate in spite of their organizational structure, not because of it. As Peters and Waterman have noted, "The very word 'organizing', begs the question, 'Organizing for what?'"

The objective is to define the most effective way to synchronize activities within the operation. Typical issues that arise in the assessment of Organization are:

-- **Scope and span of control**. Is the existing span of control proper for the unique functional responsibilities of the professional or white collar work forces?

-- **Structure and reporting relationships**. Does the structure provide clear definition of both function and responsibility to all involved? Are reporting relationships well conceived and articulated?

-- **Departmental interfaces/Functional alignment**. What are the critical interfaces among the various departments? Is the functional alignment consistent throughout the department? Are there any unnecessary barriers to communication and performance?

-- **Job definition**. Specifically, what types of individual skills will be needed in combination to collectively meet specific organizational objectives?

Process: Are we doing things right?

Process refers to the methods and procedures for individual work activities and the mechanisms by which they are linked together to produce outputs. While blue collar processes have been studied, defined, refined, realigned, and optimized, white collar processes are often a patchwork of steps which evolves over many years. The results are often just the opposite of the smooth running, efficient processes needed for high productivity. It is here that some of the immediate, higher-impact benefits can be obtained.

The objective is to define and implement the most efficient processes possible. Notice that no reference has yet been made to automation. In my experience, automation is appropriate only after a thorough process development effort has been completed. And then it may only be appropriate in certain applications. Typical issues involved in the evaluation of Process are:

-- **Work flows and bottlenecks**. Can work flow be simplified? Where are the bottlenecks? Can these bottlenecks be eliminated?

-- **Practices and procedures**. Do appropriate work practices and procedures exist? Have they been reviewed recently? Are they being followed? Can they be made more efficient?

-- **Forecasting systems**. What forecasting techniques are being used? Have they proved effective, based on experience? Are they viable, considering future needs?

-- **Coordination patterns**. What informal communication channels exist? Which channels are most effective in conjunction with formalized procedures? How can these informal channels be improved?

-- **Automation opportunities**. Which processes are prime candidates for automation? What are the costs and benefits of such an automation effort?

Motivation: Do we want to do our best?

Motivation is the human element of the model. It considers the total work environment and its role in encouraging the work force to higher levels of performance. Without such an environment, even the best mechanical efforts are ineffective.

Academics tell us that motivation is something we as managers can not create or develop directly in our work force. It is a personal attribute that can be enhanced only by each individual's desire. At best we can try to influence each person in hopes of improving his or her own personal motivation. There is no doubt, however, that this is time and effort well spent on our behalf. The returns can be significant.

Typical issues included under Motivation cover a wide scope, primarily because virtually anything could have a positive influence on personal motivation. However, the ones most commonly investigated are:

-- **Reward and recognition systems**. Are reward systems closely linked to performance? What other forms of compensation might be considered? Are informal recognition systems employed? Are they effective, and can they be improved?

-- **Communication channels**. What formal channels are available to management? To what degree are informal communication channels encouraged within the organization? How can management use such channels for the benefit of the organization?

-- **Personnel policies**. Are personnel policies well defined and communicated? Are they perceived as equitable and appropriate to all involved?

-- **Supervising techniques**. What management "styles" or techniques are used by the supervisors with their subordinates? Are they conducive to encouraging higher personal motivation? What changes can be made?

-- **Physical environment**. Is the physical environment conducive to developing a professional image within the work force? What cost effective improvements can be made to enhance that image?

A MODEL THAT FITS: THE AGENT

Thus far we have covered the four elements comprising white collar productivity: **Focus - Organization - Process - Motivation**. Yet something is still missing; the model seems static. What's

missing is the dynamic influence of management: **Management Effect**. Below we repeat the components of white collar productivity, but with one addition:

WHITE COLLAR PRODUCTIVITY

ELEMENTS

Focus	*Are we doing the right thing?*
Organization	*Are we best structured and integrated?*
Process	*Are we doing things right?*
Motivation	Do we want to do our best?

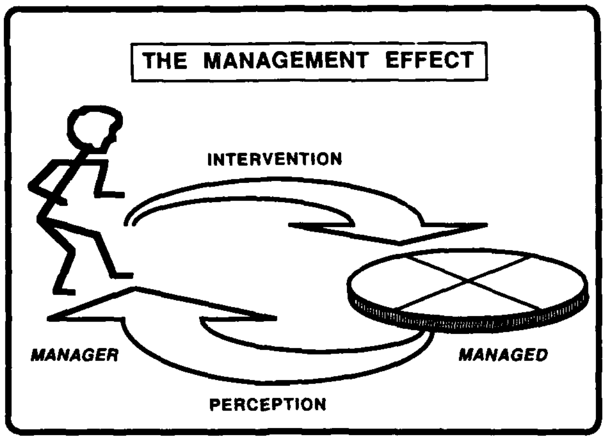
AGENT

Management Effect	*Are our perceptions clear?* *Are our interventions effective?*

Notice the fifth component at the bottom of the table: Management Effect. It is different from the other four components. Focus, Organization, Process, and Motivation are the <u>elements</u> of white collar productivity. Management Effect is the <u>agent</u> by which those elements are influenced.

Management Effect represents the dynamic aspect of white collar management, whether it is at the level of first-line supervisor, department head, or chief executive officer. In the most fundamental way, "management" comprises two legs of a loop: <u>Perception</u> and <u>Intervention</u>; seeing and changing. In the context of white collar productivity, it makes sense to characterize the Management Effect this way, because it reveals our mission: to find opportunities for enhancement and then implement them; in other words, to perceive and to intervene. Figure 3 shows this figurative loop that connects the manager with the object of management, in this case the white collar worker.

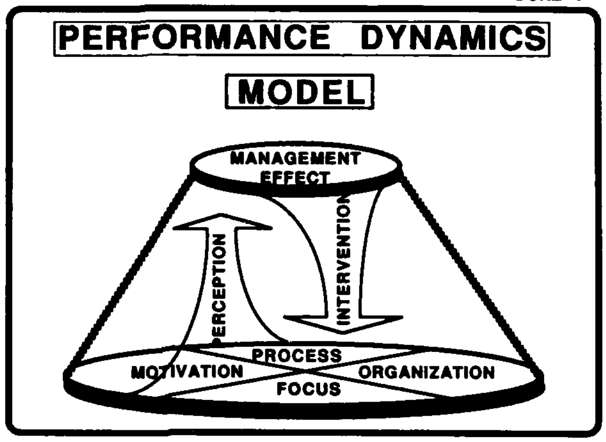
FIGURE 3



"Perceiving" encompasses monitoring performance, identifying problems, analyzing trends, and anticipating future situations. It is achieved through a range of activities, from "walking around" to formal information systems. "Intervening," on the other hand, is the act of a manager causing the change. Intervention can range from day-to-day planning, to methods changes, to personnel counselling, to reorganization.

The Management Effect, through perception and intervention, is the agent that finishes off the highly fluid, dynamic model I have set out to develop. If we superimpose the Management Effect onto the elements of white collar productivity, the result is a complete model of performance dynamics and ways to improve them. This is shown in Figure 4. The model gives us a better way of looking at white collar performance, one that helps clarify the issues and works to target the proper management intervention.

FIGURE 4



PUTTING THE MODEL TO WORK:
A CASE STUDY FROM AEROSPACE DEVELOPMENT

The usefulness of any model lies in its ability to simplify reality and make it easier to understand and manipulate. With our model, the need is the same. We need to understand how to use it and what can be accomplished with it, especially within the development environment. The following case study is based on an actual application of the model in an Aerospace and Defense company during the Full Scale Development (FSD) phase of a new, state-of-the-art aircraft program.

This major aerospace manufacturer was charged with designing and developing a completely new concept in aircraft. The firm had won this job on the strength of the its design creativity and manufacturing capability. Yet, its profitability and reputation were increasingly hanging on its ability to improve engineering cost containment and schedule adherence, particularly since past programs had suffered problems in these areas, and this contract was awarded on a fixed-price incentive basis. As one of several initiatives undertaken to reduce engineering costs and improve schedule performance, the firm turned to a white collar productivity improvement program. Let me now describe how the model was used in this environment.

Focus

As you recall, **Focus** is the link between strategy and the activities of the professional work force. This element helps determine whether detailed work activities add up to "performance" as defined by the company's overall operations strategy. For this company, the first task was to assess the costs and benefits of individual work activities, and identify those that were redundant or low in net value. Then the potential was explored for redirecting these detailed work activities to areas of higher value. Of course, any redirection could not conflict with the department's high standards for design excellence.

A review of the outputs and associated activities of the various groups did reveal areas of redundant efforts. For example, three separate groups -- Project Engineering, Manufacturing Engineering Planning, and Test and Evaluation -- were independently producing similar test schedules, each group expending significant effort to gather, analyze, and present information on test and spare parts. Consolidating these efforts to eliminate the duplication allowed a number of professionals to be reassigned to more productive activities, and enhanced communication between departments.

Another area with a Focus problem concerned Engineering estimating. As you know, the estimating group produces engineering man-hour estimates, used to price future projects. This group relies heavily on Contracts and Project Engineering for Statements of Work, which define the effort to be estimated and the type of estimate required (Firm Fixed, Budgetary, Rough Order of Magnitude). To prepare Firm Fixed and Budgetary estimates, the estimating group must receive certain information from the functional engineering groups. In this case, however, far more was being expected from the functional groups than just technical input. A review of the entire process showed that the technical specialists were devoting an inordinate amount of time to the estimating effort. In many instances, Statements of Work were actually being prepared by the functional engineering group itself, not Contracts or Project Engineering. The estimating group was doing little to support this process, with

the relevant history information. The result of all this was twofold: inconsistent estimates and excessive demands on engineering time.

To alleviate this problem, activities were redefined and reallocated in a much more rigorous manner. Structure was placed on the process itself to provide more consistency. As a result, Contracts and Project Engineering are now expected to provide Statements of Work with a defined list of input requirements and schedule dates. Engineering estimating is now required to attach relevant history to a estimating request prior to distribution. This realignment of the process addressed both the problems already mentioned; it provides for far better estimates and, even more importantly, it frees up valuable engineering time, allowing engineers to focus on producing quality drawings. Net result -- lower cost and better schedule performance.

Better focus translated to immediate savings in "found money" or found time." Also, the insights gained during the process were invaluable in building the foundation for even greater improvements.

Organization

Organization is the infrastructure through which the efforts of the professional work force are coordinated, communicated, and controlled. In this example, the demands for coordination, communication, and control were excessive. The information requirements on the FSD contract were significant. Without proper organization, on-budget, on-schedule delivery of the first aircraft could never be expected.

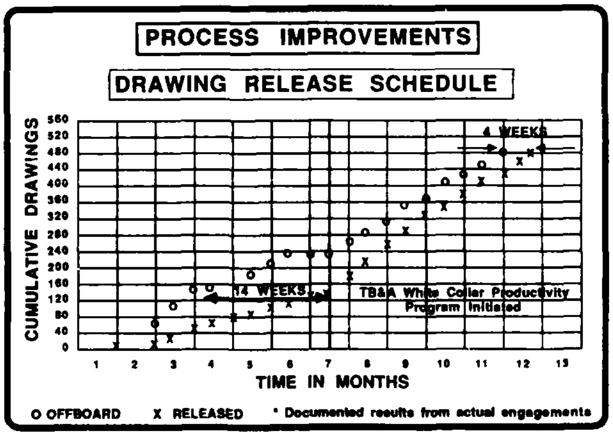
The Engineering department suffered from a familiar organizational problem. The design groups must coordinate closely with a number of "support" groups that conduct the necessary design checks. In working with one of these support groups, it became clear that its internal structure was inconsistent with the design group's. Design was organized along functional lines, while the support group was in a modified project type of structure. This created conditions of poor communication, lack of responsiveness, and inefficient transfer of information.

To a certain extent, the problem had been sidestepped through the growth of informal procedures between the groups, and through the application of excessive supervisory time to the situation. But as the information requirements continued to grow, even these practices began to lose their effectiveness. Reorganization was needed. A recommendation was adopted to restructure this support group to mirror the design group. Once this was in place, with a few more changes to group procedures and supervisors' responsibilities, the situation improved greatly. Communications were clearer, interfaces were efficient, and work flow more expedient. Net result -- better schedule performance.

Process

Process refers to the methods and procedures for individual work activities, and the mechanisms by which they are linked together to produce outputs. A critical process in aerospace design is the review and approval of engineering drawings before they are released. In Engineering, the review and approval process employed a cumbersome, somewhat antiquated, poorly defined sequence of activities involving no less than ten separate groups. Needless to say, it was plagued by bottlenecks and lack of control. Schedules for drawing review were difficult at best to maintain, and drawing status was not tracked throughout the process. Drawings were eventually released after a lengthy review cycle (approximately 14 weeks). This compounded poor communication between groups, and was devouring excessive amounts of senior Engineering management's time. The solution was to install a new and clearly defined process with discrete control and feedback points. The result, shown in Figure 5, was a 70 percent reduction in drawing approval time, from 14 weeks to 4 weeks, while maintaining the highest standards of quality.

FIGURE 5



Another example of Process improvement involves the use of automated systems. In our aerospace company, a seeming lack of access to the Computer Aided Design (CAD) terminals was causing a bottleneck in the design process. It turned out that lots of scopes were available, but utilization of the scopes was not being managed. To solve this problem, a rather simple scheduling algorithm was designed and implemented as a tool for supervisors. It immediately increased utilization by 18 percent during prime time (0800 to 1630) and by 95 percent during non-prime time (0600 to 0800 and 1630 to 1830). (See Figure 6.) This immediately eliminated the bottleneck. In fact, this seemingly minor improvement paid for the entire cost of the white collar productivity improvement program.

FIGURE 6

PROCESS IMPROVEMENTS

IMPROVED CADAM UTILIZATION

	PREVIOUS PROCEDURE	REVISED PROCEDURE
Relative Prime Time Utilization Comparison (Previous Procedure Average = 100)	100	118
Relative Non-Prime Time Utilization Comparison (Previous Procedure Average = 100)	100	194

RESULTING DOCUMENTED SAVINGS (ANNUALIZED)
21% OF GROUP TOTAL LABOR COST

** Documented results from actual engagement*

Design changes are the inevitable bane of the design process; if not properly controlled, they can be most disruptive to downstream groups. In Engineering, revisions were often made without sufficient thought given to their cost and disruption. More visibility of these impacts was needed. A new three-tiered revision process was designed to help evaluate the merits of each proposed change, as well as its impact, before it was acted upon. Once a change was deemed necessary, an on-line system for processing the change was implemented. The results were most gratifying. The processing of revisions has been streamlined significantly and the corresponding disruption reduced. Net result -- lower cost and better schedule performance.

Motivation

Motivation involves all the personal, humanistic elements of the model. With regard to motivation, a survey conducted at the beginning of the program revealed that employees did not feel encouraged to perform well, but rather to <u>avoid mistakes</u>. Negative reinforcement was a predominant management technique. Employees heard from superiors if something went wrong, but rarely if something had gone well. A supervisory training program was proposed to help develop a more creative and positive environment.

High turnover is often an indicator of motivation problems. In this case, there was a turnover problem with the more junior professional staff. A significant source of this problem was traced to the performance rating system. It operated on a 1 to 5 scale (1=low, 5=high), with a normal distribution of ratings expected across the department. Upon investigation, it was noted that everyone in the department was being evaluated relative to everyone else. Little, if any, distinction was made for labor grades or experience levels. The outcome was that approximately 90 percent of the more junior professionals were receiving 3's, while the 4's and 5's were reserved for managers or technical specialists. The obvious solution of rating within grade level was recommended, with two anticipated effects. First, it would improve the morale among the younger professionals and provide each with an opportunity to differentiate himself or herself based on performance. Second, it would provide a strong signal to the managers. No longer would a manager's title guarantee a high performance rating. Net result -- lower cost.

Management Effect

Management Effect involves both perception and intervention. One of the toughest hurdles for white collar productivity improvement is the misconception that defining a work force as "professional" means that it does not have to be managed. On the contrary, productivity will never improve unless

management is capable of clear perceptions and effective interventions. This entails monitoring activities and results, identifying problems, taking corrective action, assessing the effectiveness of the action, and providing feedback on the need for other changes in the elements of productivity.

Yet in Engineering, the information necessary for good project management and coordination many times was not available in the proper form, or was not readily accessible. Two separate tasks were undertaken to try to improve this situation. The first is still in its implementation phase. A critical path scheduling system was developed to provide greater project visibility. With it, complete schedules with immediate need dates, task sequencing, and task interdependencies will now be available. These schedules should replace the tools now being used, which are really nothing more than automated drawing lists. Management then will have a sophisticated tool to provide timely, reliable information on task status. This system is expected to be of great benefit on future programs as well.

The second task was the design and implementation of a milestone system for tracking Engineering Work Authorizations (EWAs). Roughly, the previous system had been developed around the concept of one EWA per engineering deliverable (i.e. drawing, report, etc.). This system had proved adequate on earlier, much smaller programs, but was being overwhelmed by the information requirements for this FSD contract. Paperwork was mounting rapidly. Managers were having a difficult time maintaining cognizance over all the various tasks. The new system relieved the paper burden by consolidating related tasks on one EWA. Budget requirements for each task were provided but were tracked at the EWA level. Management reports were changed to reflect this modification. However, no changes were necessary in the already government-validated Management Control System (MCS). This new system is expected ultimately to reduce paperwork by at least 67 to 75 percent with no reduction in project management capability. Net result -- lower cost and better schedule performance.

Results

This white collar productivity improvement program was considered a success by everyone involved. In the Airframe Design area, the total design time was reduced by approximately 25 percent and produced a cost avoidance savings of over $8.0 million. This number is based only on the improvements that could be quantified easily. Many of the more difficult-to-measure benefits are not included. These results were accomplished with no additional capital investment; what's more important to note, the benefits are in fact sustainable. The people now are confident in their ability to make improvements, and are focusing on the future.

ON IMPLEMENTATION

To bring this paper to a logical conclusion, brief mention must be given to implementation. Once you've taken the initial step to understand the model and how it can be used in a situation like the case just described, the next step is to develop a capability to use it to address productivity issues in a sustainable manner. To date, little research has been conducted on the factors that determine the effectiveness of productivity efforts. Therefore, I base most of my comments on my direct experience, the questionnaire responses, and the personal interview data on the current practices of others.

I have found six key components of successful implementation:

1. Top Management Involvement

This point has been made before, but I don't believe it can be stated enough. An effective productivity improvement effort requires forceful, continuing, and visible support from top management.

The primary obstacle to implementing a successful productivity improvement program is internal organizational politics. As one well known behavioral scientist put it:

> An organization that wants to change can. But by itself, productivity is not a sufficiently moving cause to create that desire. What makes or breaks a productivity program is the power of its advocates. Most organizations are not democracies: the opinions that move them are concentrated in a small group of top and middle managers. These people are not dictators: they respond with considerable inertia to what their leaders command. A productivity improvement program -- or for that matter, any change -- that fails to take account of these realities is doomed.

2. An Influential Leader

The manager of an internal productivity effort must have significant organizational "clout" or influence. Virtually all productivity efforts operate in a staff capacity. The productivity manager, therefore, with limited functional authority, usually small staff, and modest budget, must be quite resourceful. This person must have strong functional skills and, even more importantly, must be organizationally and politically savvy.

Organizationally, it is advisable that the manager of the effort report directly to the senior manager of the department, or possibly the corporate president. This goes back to my comment on organizational "clout." Even the most influential and personable leader needs support. This support must come from the top. Without it, the results, unfortunately, are easily predictable.

3. Start Slow/Grow With Success

One of the most widely observed mistakes that companies make when they initiate a program is trying to undertake too much at once. Managers have gotten into the habit of expecting productivity improvements to come from some single large breakthrough. It doesn't work that way. And even if it did, the chances are small for a successful initial implementation effort on a large project involving multiple tasks and many individuals.

It is advisable to start the effort simultaneously along a limited number of fronts, rather than focusing exclusively on a single project. The chances of a success are much higher. The long-term sustainability of a productivity improvement program depends on the credibility it gains in the early stages. Find those projects that show promise, and let the effort then grow with your successes.

4. Employee "Buy-In"

Many times the difference between success and failure in implementation is the difference between "my idea" and "our idea." By this I mean if the employee knows he contributed in the initial design of a change, then he feels a sense of ownership in the success of its implementation. This type of involvement usually means it takes longer to finish the initial design of a change, but I can assure you it significantly reduces the time necessary to implement it.

In working toward employee involvement, the most important skill to apply is that of effective listening. You shouldn't expect to know more about a particular situation than the person who lives it every day. Listen to his perspective and incorporate his thinking with your own. Not only will the people involved feel a part of the change effort, but the final result is usually better conceived and easier to implement.

5. Long Term/Short Term Perspective

My comment here differs somewhat from traditional thinking. Most academics preach the need for a long-term perspective on productivity improvement. As one observed: "Industry didn't jump into a productivity slump. We worked our way into it slowly over a number of years, and we are going to have to work our way out of it in about the same way." I don't disagree. Moving an organization toward a common set of goals is an extremely difficult task. It usually requires a cultural change, which means changing attitudes, skills, and behaviors. This takes time.

Yet, I would like to add another perspective based upon my experience as a management consultant. Clients expect and deserve a return on their investment from your services. To overlook this requirement is short-sighted. The same is true with a productivity effort driven from within. The organization is your client, and the client expects a return. Therefore, don't focus exclusively on the issues that will take months or years to resolve. Chances are you may not be around to see the outcome.

When rank ordering the improvement projects to be undertaken, include a small number that can obtain immediate results. Use these to "fund" the longer-term efforts that will provide you with even greater benefits. Thinking about projects in this manner is an effective strategy for sustaining a long-term, viable program.

6. Reluctance to Change

Although it is appealing to think of organizations as rational structures populated with logical people working toward shared goals, this view is unrealistic. Organizations in many cases are political battlegrounds where individuals maneuver for power and influence. Therefore, many seemingly logical changes that could benefit everyone are sometimes thwarted by individuals seeking to enhance or protect their own power base. They will say, "I've worked hard to get where I am today, and I don't want anyone changing things now."

This sort of viewpoint is understandable. People do, indeed, work hard to reach their existing levels of influence. Therefore, one cannot expect them to change easily. *This perspective must* be kept in full view at all times. Let me offer a few suggestions as to how one works effectively with these people in such environments:

-- **Don't be hesitant.** Express your desire and need to work together.

-- **Find common ground.** Explore ways to make change a "win-win" proposition.

-- **Identify your allies.** In the face of adversity, knowing who your friends are is invaluable.

-- **Publicize your successes.** Expound on the benefits realized through your collective efforts. Give credit to everyone involved.

CLOSING COMMENT

Designing, initiating, and sustaining a productivity improvement effort is a most difficult task. It requires both a well-tested framework for approaching change and a proper perspective toward implementing it. It is my hope that this paper has provided each of you with a better understanding of both these issues. The benefits are there and I wish you the best of luck in obtaining them. Thank you.

THE EFFECTS OF TWO CARLUCCI INITIATIVES CONCURRENCY AND STREAMLINING, ON THE TEST AND EVALUATION PHASE OF SYSTEM ACQUISITIONS

by

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BACKGROUND

The first acquisition of a major weapons system for the U.S. Government started with the authorization for the procurement of six large frigates by the U.S. War Department in 1794. Seventeen months later six keels were laid but only three of the frigates were built due to schedule slippage and cost overruns (25:p.I-1). In more recent times, centering around World War II, the mode of acquisition was to develop, test, and produce aircraft almost simultaneously, the resulting aircraft were delivered only to falter at the front lines with deficiencies that restricted full operational use. Subsequent to WWII, the testing of development models was done under phase testing followed by category testing, the U.S. Navy calling the test periods in category testing Navy Preliminary Evaluations(NPE). Operational test was to be included but faults were found in the approach to operational suitability testing (24:p.8). Of more concern, however, was acquisition concurrency between the production capacity build up and the testing process. The result was production efficiency early in development but system deliveries occurred before completion of testing. Deficiencies found as the result of testing could not always be incorporated in the early production systems and restrictions on operations were placed on the aircraft as they were fielded (24:p.8).

A study by a blue ribbon defense panel in 1970 which had conducted a review of the acquisition process recommended, "appropriate planning early in the development cycle for subsequent tests and evaluations and effective transition to the test and evaluation phase," and "a general rule against concurrent development and production, with the production decisions deferred until successful demonstration of developmental prototypes" (24:p.9). From that study came the policy of determining operational suitability prior to the production decisions, the so called "fly-before-buy" policy.

As a result of that change in policy, there was a significant increase in the length of the acquisition process because the development, test and evaluation, and production phases were directed to be in series instead of in parallel or concurrent. Toward the latter part of the 1970s the Defense Science Board Summer Study, chaired by Dr. Richard DeLauer of TRW, Inc., brought this stretch-out into focus. Appendix I shows the dramatic increase in the engineering man-days for just the contract design phase for some recent Navy ships (25:p.I-3).

In 1980 the Department of Defense (DOD) Instruction 5000.2 was promulgated which included the statement, "Consideration (should be given to) acquisition cycle time by planned concurrency. This may include increasing funding, overlapping, combining or omitting the phases of the acquisition process or overlapping or combining developmental test and evaluation (DT&E) with operational test and evaluation (OT&E). The amount or degree of such concurrency should be keyed on the extent of the potential savings in acquisition time balanced against technical, cost and supportability risks and national urgency in each acquisition program" (25:p.I-3). The recent revision of DOD Instruction 5000.2 does not address the subject of concurrency (13) but it is well described in DOD Directive 5000.3 (14:pp.4-5).

As there was growth in the length of acquisition, there was a parallel growth of government involvement in telling the contractors how-to build as well as what-to build. There was a tendency to expand on the scope of the references to specifications and standards in the solicitation process, the government providing those documents which often went into detail on how to build what the government was soliciting. Since the defense standardization and specification program (DSSP) was established in 1952 to improve the operational readiness and cost-effectiveness of defense material, there has been a growth to 45,000 active standardization documents today. Currently in support of the DSSP there are more than 7,000 standardization projects underway or planned (26:p.43). A significant number of those standards and specifications are now references in the acquisition arena which dictate how industry is to build or make contract delivery items.

In 1981, Mr. Carlucci, then the Deputy Secretary of Defense, published his thirty-two initiatives aimed at improving the acquisition process. The list in shortened form is presented in Appendix II (24:p.15). Of the thirty-two initiatives, two are having a significant effect on the test and evaluation of full scale weapon systems and it is with the above background in mind that we will address those two in the remainder of this paper. The first is number 12, "provide front-end funding for test hardware" and the second is number 14, "reduce the number of DOD Directives." The rest of this paper will address their impact on the acquisition of U.S. Naval Aviation weapon systems.

CONCURRENCY

As previously mentioned, concurrent development test and production were occurring in the 1950s. Today concurrent activities are focused on the events of development that can be done in parallel, such as development and operational testing. Concurrency is not specifically defined in the guidance from the Department of Defense to its Military Service acquisition activities. Nevertheless, the program is clearly spelled out in DOD Directive 5000.3, last promulgated in 1986. In part it says,

"Combined Development Testing and Operational Testing (DT&E/OT&E): A combined DT&E and OT&E approach may be used when cost and time benefits are significant and are clearly identified, provided that test objectives are not compromised. Planning for such a testing approach shall be coordinated early during the test concept definition and designed so that resources are used efficently to yield the data necessary to satisfy common needs of the developing agency and the Operational Test Authority (OTA). This requires that data bases be established and maintained to support progressive test and evaluation events during all phases of the acquisition cycle. Participation by the OTA in the planning and execution of tests must ensure that the testing conducted and data collected are sufficient and credible to meet the OTA's requirements. Any combined test program chosen shall contain enough dedicated operational test events to satisfy the OTA requirement for an independent evaluation. The final period of testing before the full production decision shall emphasize appropriate, separate OT&E managed by the OTA. In all cases, separate independent development and operational evaluations of test results shall be provided."(14:p.8).

The key aspects to this guidance are the provisions, "... the necessary resources, test conditions, and test data..." In order to meet these provisions necessary to support concurrent testing the program manager and his staff must do a trade-off study between schedule and the cost of incorporating these provisions (25:p.II-3). Obviously, for combined and/or concurrent test to occur, the ranges, weapons, test articles, data collection and reduction devices, aircrews and ground support equipment must be available in sufficient quantities to permit the simultaneous testing by both the development and operational testers. The reference to concurrent testing in the DOD guidance is fairly specific in the resources necessary to conduct concurrent testing. Carlucci Initiative Number 12 emphasizes the requirement to fund the test resources early in the program in order to have the flexibility in the schedule to plan concurrent DT&E and OT&E. The new guidance is allowing the program managers to plan for funding of the test resources necessary for concurrent testing in order to reduce the extended acquisition cycles that have been a concern for the past several years. The visibility of the program planning and strategy formulation at high levels in the DOD is requiring the program manager to do risk analysis on their program to ensure that the consequences of planning concurrency in test and evaluation are taken into consideration.

STREAMLINING

Streamlining has its foundation in the Carlucci Initiative Number 14, "Reduce the number of DOD Directives, and eliminate non-cost-effective cortract requirements" (2:p.21). While this initative is very specific in nature towards the DOD Directives, it was not as clear towards the direction it was to take in contract requirements. In a series of memoranda from December 1984 to June 1985, Deputy Secretary of Defense, William H. Taft, IV, took the lead in identifying the problem and giving direction to the services to eliminate non-cost-effective contract requirements, to which the term streamlining has been applied (26:p.58). The thrust of his effort was to reduce the layering of specifications and standards in the acquisition process, to reduce the "how-to" direction in the DOD requests for proposals and contractor oversight, and to encourage the use of non-development items (NDI), those commercially available systems from the U.S. or off-shore that have adequate performance to meet the DOD requirements.

Momentum towards streamlining is growing. It is a natural for a program manager because the effects of the initiative reduce cost and can improve schedule. However, the "not-invented-here" syndrome and the rice bowl mentality are potential obstacles to be dealt with in the building of the support for utilization of streamlining. The essential ingredient in the support for streamlining is a shift in attitude by the government heirachy that must agree with the effects of streamlining a program (30). In the case of streamlining there is very strong leadership from the top. Initially there were only three Naval aviation acquisitions assigned to be scrutinized for streamlining implementation. Several others have been added and now there is a Specification Control Advocate General within the office of the Secretary of the Navy through which all large acquisitions must pass and gain concurrence for approval. Most programs managers have taken the initiative on their own because of the potential for cost savings and schedule improvements that can be realized.

It is only very recently that a directive has been signed out of DOD implementing the streamlining initiative. However, it has been utilized in various draft forms from the beginning of Secretary Taft's memorandums. In the current DOD Directive 5000.43, the definition of streamlining is

"Acquisition Streamlining. Any action that results in more efficient and effective use of resources to develop, produce, and deploy quality defense systems and products. This includes ensuring that only cost-effective requirements are included, at the most appropriate time, in system and equipment solicitation and contracts." (15:p.2-1).

The directive requires specifying contract requirements in terms of the results desired, rather than "how-to-design" or "how-to-manage," precluding premature application of design solutions, specifications, and standards. In essence tailoring of contract requirements to unique circumstances of individual acquisition programs, and limiting the contractual applicability of referenced documents to only those that are essential is now mandatory.

Figure 1 shows in a graphic form the proper evolution of technical requirements through the phases of acquisition (11:p.15). In the early phases of the acquisition cycle, there should be very few predetermined detail designs and limitations on the development of alternatives. As each phase brings into focus the design that optimally provides the solution to the requirements, only then should technical design be allowed to be directed, primarily to enhance configuration control as the design proceeds to maturity. From another perspective, there has been a tendency to reference specifications and standards which in turn reference other specifications and standards in a pyramiding effect as shown in figure 2 (7:p.6). Streamlining is specifically aimed at reducing this pyramid. In the U.S. Navy programming documentation, two layers of specifications and standards are the maximum that can be imposed prior to production.

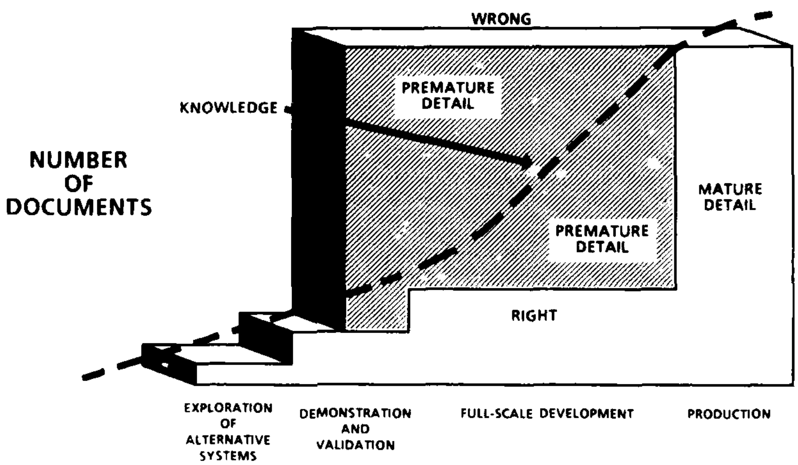
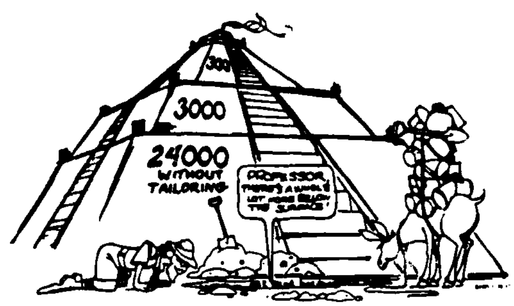


Figure 1
THE EVOLUTION OF TECHNICAL REQUIREMENTS



If it's important enuf to be contractual,
it's important enuf to be named/numbered

Figure 2
PYRAMID OF REFERENCES

The impact on the test and evaluation phase of acquisition by streamlining's reduction of specification references has yet to be realized because of its recent application. The programs that have been targeted for streamlining have gone through the reduction in specification tiering but none have reached the testing phase. From the perspective of the tester, there will be little difference except where facets of testing have been deleted from the test program because of similarity with other end items or risk of test elimination is low. It is becoming apparent that the tester will have to participate earlier in the development to understand the design concepts and requirements in order to develop adequate test plans because reliance on previous methods of test may no longer be applicable (32). It appears that streamlining may provide an impetus to the further incorporation of concurrency in test as program managers trade-off cost for more resources to reduce schedule in the testing phase of acquisition programs. This is obviously a form of streamlining. Important in the decisions to streamline and/or increase concurrency in a program is the increase in risk, a subject to which the paper will now turn.

RISK ASSESSMENT

There is very little literature that provides guidance to the program manager on how to make risk assessments or how to do trade-off studies for the effects of concurrency and streamlining. In September 1982 a study was done for the U.S. Navy which developed a risk taking analysis and methodology as applied to the risks associated with concurrency (25). More recently, a guide published by the Department of Defense called The Transition to Production described templates to guide the transition from development to production in which the test and evaluation process is amplified as a risk taking concern for a program manger. In this past year the U.S. Navy has established a course to implement the streamlining initiative. In that course risk analysis is covered in some detail.

In order to make an assessment of the risks associated with concurrency or streamlining, there must be a willingness to accept the consequences of taking a risk, most often manifested by an increase in near term costs to shorten the schedule (25:p.III-3). In the early planning of an acquisition, a baseline is established within a given minimum of people, facilities and funds. In simple terms the program manager then adds funds to increase the people and facilities applied to the acquisition which in turn allows the program to have concurrent activities and reduce the how-to directions to the contractors and thereby shorten the schedule.

The questions that the program manager has to answer in the planning phase are, "Is the system mature enough to impose specifications and standards without losing a better solution? Have I enough information to streamline the testing requirements? and Are the risks low enough to impose concurrency of test and evaluation?" The risk must be low so that there will not be a test result that will defeat the fielding of the system on time. The Defense Science Board noted that programs are not cancelled for the reasons of concurrency but rather for reasons of a technical or political nature, or because requirements change (25:p.I-3).

In order to be able to look at deviation from a baseline which is considered to contain the optimum contributions of cost, schedule and performance, the program manager must have the ability and willingness to accept a non-zero chance of missing the funding level or time estimate. For example, if a program has a 40 month baseline with a 10% chance of missing schedule, then additional funds can provide test resources to support test concurrency and test requirements streamlining and maintain the same level of risk. Alternatively, for the same resources, the program manager can accept a higher level of risk and also shorten the schedule. Appendix III lists the seven steps of the concurrency analysis model developed for the U.S. Navy (25:IV-4).

In the development of the acquisition plan the program manager spends considerable effort generating support for his approach to concurrency and streamlining. Once he has established the plan and begins its execution, there is a tendency for the support to dwindle as the program proceeds. As a consequence, when the schedule is missed or there is a requirement for more funds, the program manager is on his own, finding that support is lacking when it was there in the beginning (32). In addition, there are other significant hurdles which inhibit the application of concurrency in test, hurdles which arise as the program moves through its acquisition cycle. The first and foremost of these potential conflicts with the implementation of streamlining and concurrency is the importance of the test and the feedback of test deficiencies to the design group for analysis and correction. In subsystem design significant strides have been taken to improve the test process. In reliability testing there is a process called test, analyze and fix (TAAF). This process takes the time to test at accelerated rates to determine weaknesses in the design and manufacturing of procedures in order to improve the reliability of a subsystem. This process also should occur in the full system test phase, but there the complexity of the system requires significant increases in resources for each iteration of the TAAF loop (33). Computer driven simulations and stimulations are reducing the risk of limited resources for full system test but there are still design deficiencies arising from full system test that require redesign and subsequently affect schedule and cost.

Another factor important to risk taking associated with concurrency and streamlining is the independence of the operational test and the establishment of the Office of the Director, Operational Test and Evaluation (DOT&E), within the DOD, reporting to The Secretary of Defense and Congress. His position is to have oversight of the Military services' operational test for selected programs. Operational realism in operational test with engineering development models built in full scale development is creating higher risk than previous approaches to concurrency of test. In summary DOT&E is a new player that has to be dealt with as a strong participant from early planning to the fielding of a new system.

COMMENTS ON RESULTS TO DATE

The current typical program structure is shown in Appendix IV. It shows the milestone decision points for which development and operational test results are required (DT and OT respectively). It shows the production order points for limited quantities concurrent with development and shows DT concurrent with OT except for the final phase of OT called the operational evaluation (OPEVAL) which is separate and distinct from the other aspects of development.

Several major acquisitions have completed their prescribed program structure test and evaluation phases since the Carlucci initiatives were promulgated. In each there were concurrent activities in the testing which contributed to the success of their full scale development. Many of the less than major acquisitions are also completing their test phase under the initiatives of Mr. Carlucci, most of them achieving some degree of success in compacting schedule as result of concurrency of testing or some other aspect of the acquisition cycle.

The F/A-18 Hornet was the first full system development that was principal sited at a single location by the U.S. Navy for the majority of the flight test, in this case NATC, Patuxent River, Maryland. The rationale for the principal siting was the reduction in duplication of resources and the collection of a single set of data by both the contractor and the U.S. Navy. In the case of the Hornet, the operational testers were also co-located at NATC for initial operational test and evaluation, providing an opportunity for all three types of testers to participate in the collection of data to support the conclusions that the aircraft met the requirements it was designed to meet. Post test analyses generally show that the concept of principal siting was effective from the aspects of resource streamlining, cost savings and schedule compaction. In addition, some contractors have maintained that moving the aircraft away from the design and manufacturing site resulted in delays in data analysis and subsequent corrective actions. Since the aircraft has been fielded it has demonstrated readiness and maintainability almost twice as good as its sister tactical aircraft. From an overall U.S. Navy perspective, the concurrency implemented in the Hornet acquisition has proven successful because the system was fielded on time with quality.

The AV-8B Harrier acquisition was another program that was principal sited at NATC in order to achieve the same economies of cost and schedule as the Hornet. In the case of the Harrier, the design concept was to take the existing Harrier engine and design a new airframe and weapon system around the engine. As the program moved through full scale test, the engine did not perform as predicted. With the cooperation of the operational test force, the operational testing was divided into two phases, giving the program manager the time to fix the engine performance prior to the final phase of operational testing. Without the concurrency of the operational testing and the prior schedule compaction, it would have been necessary to terminate the Harrier test phase until the engine performance was improved, at an increase in cost of $100 million. There was significant risk assumed with the approach that was taken if the engine performance did not improve in time to commence the second phase of operational testing. There was also concurrency in the test and limited production of the aircraft. This provided field assets from a pilot production and two limited production lots. The mark of the success of this acquisition was the comment made to the program manager by the Commander, Operational Test and Evaluation Force, that the operational test of the AV-8B was the best for an aviation system that he had experienced in his tour (31).

A third example of the concurrency in the full scale test and evaluation phase is that achieved by the SH-60B Seahawk. The airframe in that program is similar to the U.S Army's Blackhawk so that limited testing could be achieved without compromising the importance of test results. The main test effort focused on the test of the total mission systems, both the aircraft and ship connected together by a data link in an anti-ship and anti-submarine suite. Again, in this acquisition the principal site of the testing was NATC for testing the avionics suite integration efforts of the contractor. The utilization of the NATC resources maximized the savings in schedule and cost of testing. In addition, the co-location of the operational test squadron at NATC provided a unique opportunity to have concurrent testing.

In each of these full system test and evaluation phases there was risk associated with the concurrency and streamlining efforts that preceded the testing. However, the risks were minimized by the program managers and considerable savings were achieved by trade-offs made from the original baseline for the programs.

THE FUTURE

Many of the initiatives that were set into motion by Mr. Carlucci have taken root and are implemented. As demonstrated by the F/A-18 Hornet, the AV-8B Harrier and the SH-60B Seahawk, concurrency in the test and evaluation phase of full scale development is taking hold as a way of improving on schedule or to provide relief for the correction of deficiencies found in testing. The full effect of specification streamlining on the test and evaluation phase has yet to be determined. Every program manager is implementing the initiative but few systems have had time to reach the test and evaluation phase. However, one program underwent its streamlining in 1985 due to a cost cap imposed on the program by the Secretary of the Navy. The consequence of this streamlining effort is shown in figure 3 (22:1.0:VIEWGRAPH).

	BEFORE	AFTER
FSED CONTRACT TYPE	CPIF	FFP
GROUND TEST ARTICLES	3	2
FLIGHT TEST AIRCRAFT	4	2
FLIGHT TEST HOURS	913	701
DATA REQUIREMENTS	530	251
SPECIFICATIONS	322	281

Figure 3
DEVELOPMENT PROGRAM COMPARISON

The T-45 Undergraduate Jet Flight Training System was initially baselined at about $728 million. The Secretary of the Navy set a cap at $450 million after which the program manager and his team, including the contractor, scrubbed various components of the program to eliminate cost (26:p.61-64). The result is shown in the right column of figure 3. The final cost of the current development program is $438 million, $12 million under the target. The reduction in cost was not without risk in that two test articles will limit the time available to correct deficiencies, reduce the potential for concurrent test activities and reduce the scope of testing during the test and evaluation phase. However, the aircraft itself is a modification of an aircraft already in use by the British and therefore has a significant amount of test data available which can be translated across to the U.S. carrier based version. A major part of this system is the training support system that goes with the aircraft, a new concept in the fielding of a training system. The testing of this support system will be new for the contractor and for the U.S. Navy. In the case of this system the operator is the training command, a newcomer to the test and evaluation phase of acquisition.

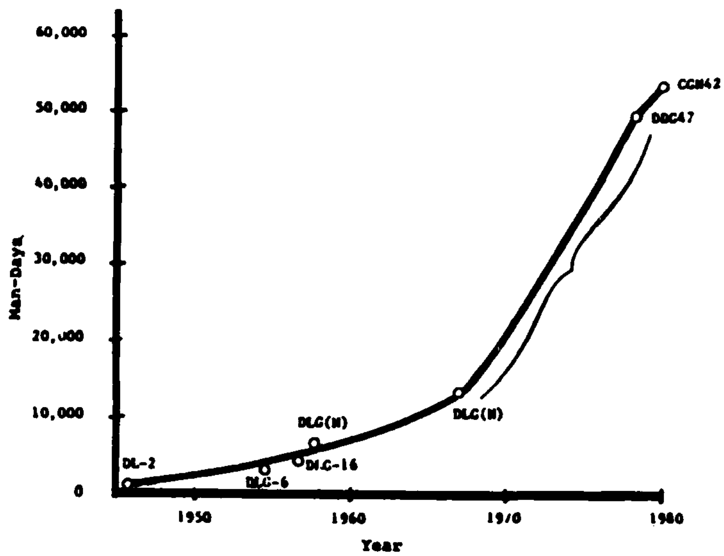
The V-22 Osprey acquisition program has reduced the references to specifications and standards by an equivalent of $350 million. The references to specifications and standards is limited to two tiers with further references being advisory in nature only. The program manager, realizing that he was taking a significant risk, required the contractor to fix the deficiencies found in development testing of a given severity and also to fix the critical and major deficiencies found in operational test at no additional cost to the government. In addition, the government is participating in every aspect of the full scale development and has the military test pilots participating in the flight test data collection effort starting after the first 25 flight hours have been accumulated. Thus risk was taken by streamlining but further steps were taken to reduce the risk to the government that could occur from the contractor building to a performance specification and a limited detailed specification (31).

In another program, as a consequence of streamlining, the government has imposed strict performance, warranty and reliability contractional clauses to further protect the interests of the government. Comprehensive test and evaluation will be, therefore, a critical element in determining compliance with these contractural clauses. As written in the requests for proposals, failure to meet the specified parameters in these specific clauses will result in further design, development and test tasks on the part of the contractor at his own expense (34).

The initial efforts at concurrency and streamlining are having a positive effect on the major programs so far as the initiatives are implemented. Risks are being taken by the program managers that are methodically determined through trade-off analyses. There are concerns that the risks being taken may not be supported by those who are their advocates when the risks taken result in a schedule slip, a performance limitation or cost overrun. The program manager is the responsible individual for implementing the initiatives and also has to bear the burden of failure to meet the triple constraint of cost, schedule and performance even though he is executing policy and guidance set by higher authority. There is need for a tying policy that provides an audit trail to those who required the program manager to execute policy that looked good in the planning but proved to be higher risk in meeting the requirements of the triple constraint than was predicted.

SUMMARY

History has swung through the arc of a pendulum with the post WW II concurrent test and production at one apex and the 1970s fly-before-buy at the other. As a result of two of the Carlucci initiatives, manifested in concurrency and streamlining, the pendulum is currently moving back toward more concurrency, particularly in the attempt to have concurrent test and evaluation by the various testers. Streamlining is being implemented in all programs, but there has not yet been a program that has gone through the full acquisition test and evaluation phase having been streamlined from its initiation. Both initiatives have brought savings in cost and abbreviated schedule but there is concern that the support infrastructure which required the execution of the initiatives may not be in place when the program does not meet its cost schedule or performance requirements.



Source: "The Changing Nature of the US Navy Ship Design Process," Robert S. Johnson (1980). Course Material from the Navy Ship Design Process Course, The Catholic University of America.

Exhibit I-1. MAN-DAYS OF EFFORT TO PERFORM THE CONTRACT DESIGN OF VARIOUS DESTROYER TYPES OVER THE LAST 30 YEARS

1. Reaffirm Acquisition Management Principles
2. Increase Use of Preplanned Product Improvement
3. Implement Multiyear Procurement
4. Increase Program Stability
5. Encourage Capital Investment to Enhance Productivity
6. Budget to Most Likely Costs
7. Use Economical Production Rates
8. Assure Appropriate Contract Type
9. Improve System Support and Readiness
10. Reduce Administrative Costs and Time
11. Budget for Technological Risk
12. Provide Front-End Funding for Test Hardware
13. Reduce Governmental Legislation Related to Acquisition
14. Reduce Number of DOD Directives
15. Enhance Funding Flexibility
16. Provide Contractor Incentives to Improve Reliability and Support
17. Decrease DSARC Briefing and Data Requirements
18. Budget for Inflation
19. Forecase Business Base Conditions
20. Improve Source Selection Process
21. Develop and Use Standard Operation and Support Systems
22. Provide More Appropriate Design-to-Cost Goals
23. Implement Acquisition Process Decisions
24. Reduce DSARC Milestones
25. Submit MENS with Service POM (MENS nor JHSNS)
26. Revise DSARC Membership
27. Retain USDR&E as Defense Acquisition Executive
28. Raise Dollar Thresholds for DSARC Review
29. Integrate DSARC and PPBS Process
30. Increase PM Visibility of Support Resources
31. Improve Reliability and Support
32. Increase Competition

(2:55)

Figure 1. Acquisition Improvement Actions

APPENDIX II

Step 1. Construction Baseline Schedule
- 1.1 Develop Project Schedule Philosophy
- 1.2 Construct Baseline Networks
- 1.3 Identify Potential Concurrency Options
- 1.4 Develop Structure of Risk Evaluation Checklists

Step 2. Evaluate Funding and Schedule Constraints
- 2.1 Determine Significance of Constraints
- 2.2 Determine Scope of Concurrency
- 2.3 Relate Constraints to Concurrency Options

Step 3. Determine Motivation of Concurrency: Schedule Protection or Schedule Compression
- 3.1 Determine Extent of Internal Program Limitations
- 3.2 Refine Baseline Schedule Estimates
- 3.3 Reevaluate Preceding Decisions
- 3.4 Develop Initial Set of Risk Evaluation Checklists

Step 4. Determine Degree of Acceptable Cost Risk/Schedule Risk
- 4.1 Develop Final Baseline Resources and Schedule Estimates
- 4.2 Determine Acceptable Degree of Concurrency
- 4.3 Determine Acceptable Degree of Risk
- 4.4 Review Remaining Concurrency Options

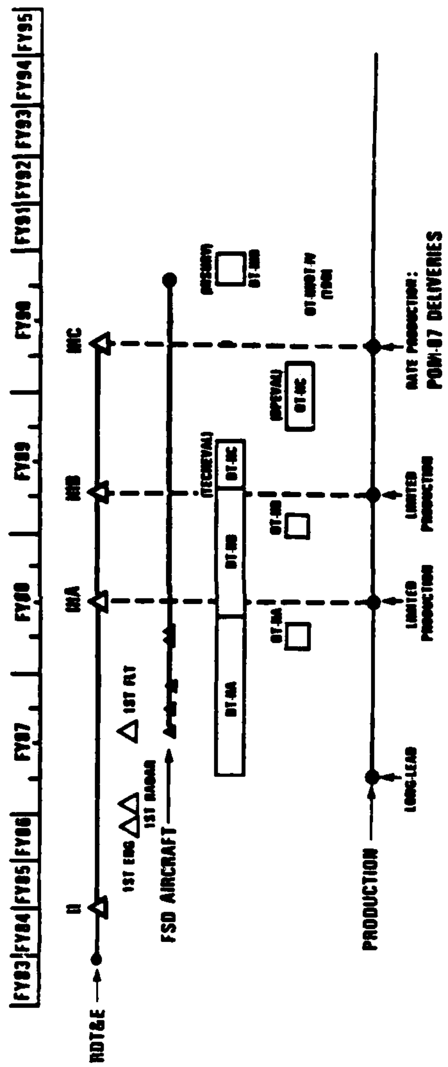
Step 5. Develop Alternative Schedules
- 5.1 Select Constrained Concurrency Options to be Used in Developing Alternatives
- 5.2 Group Concurrency Options for Development of Alternatives
- 5.3 Generate Alternative Schedules
- 5.4 Determine Critical Path for Each Alternative

Step 6. Evaluate Risk for Each Alternative
- 6.1 Finalize Evaluation Checklists
- 6.2 Apply Checklists to Detailed Schedule and Subschedules
- 6.3 Score Each Alternative Based on Cost and Schedule Risk and Response to Constraints
- 6.4 Aggregate Data to Decision Making Level of Detail

Step 7. Select New Schedule
- 7.1 Review and Revise Decision-Making Criteria
- 7.2 Review and Revise Proposed Schedule-Monitoring Techniques
- 7.3 Analyze Results of Risk Analysis of Alternatives
- 7.4 Apply Decision-Making Criteria to Viable Alternatives
- 7.5 Select Alternative
- 7.6 Revise Existing Schedule

Exhibit IV-3. STEPS IN CONCURRENCY ANALYSIS MODEL

PART II PROGRAM STRUCTURE



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ACCELERATION DU DEVELOPPEMENT DES PROTOTYPES ET REDUCTION DES COUTS PAR INTEGRATION PLURIDISCIPLINAIRE

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RESUME

Depuis sa fondation la Société AMD-BA a réalisé 92 prototypes, le dernier né étant le RAFALE, démonstrateur de technologies nouvelles, préfigurant l'avion de combat futur. La politique industrielle de la Société, poursuivie avec continuité et persévérance, a toujours été d'effectuer un développement et une mise au point ultra-rapides, suivis d'une industrialisation réalisée dans des délais extrêmement réduits, tout en assurant une haute qualité du produit.

Devant la complexité toujours croissante des avions modernes, une telle orientation n'a pu être maintenue que par la mise en place d'une organisation adéquate et de moyens techniques originaux.

1 - L'EXPERIENCE

Depuis plus de 40 ans, la Société des AVIONS MARCEL DASSAULT-BREGUET AVIATION (AMD-BA) a construit son renom grâce à la qualité de ses produits tant en aviation d'affaire, qu'en aviation militaire et, à sa rapidité inégalée dans la réalisation des prototypes, leur mise au point, et la sortie des premiers avions de série.

Sans vouloir rentrer dans trop de détails qui pourraient apparaître fastidieux, il ne m'apparaît cependant pas inutile, en quelques chiffres, de rappeler ce que représente notre Société.

Depuis quarante ans, les AMD-BA ont produit 6.000 avions militaires ou civils et ont exporté leur production dans 60 pays. La production des AMD-BA recouvre de manière continue une gamme élargie d'avions d'affaires et d'avions militaires dont la variété s'étend pour ces derniers aux avions de défense aérienne, d'attaque au sol, d'entraînement, de l'aéronavale, de pénétration supersonique ou, et le plus souvent, d'avions multirôles.

Les deux premières planches imagent assez nettement l'étendue de nos exportations dans l'ensemble des pays du monde, pour les familles des avions MYSTERE, MIRAGE et ALPHA-JET.

Le volume de ces exportations est représenté sur la planche n° 3 qui fait apparaître, en valeur moyenne, qu'en l'espace de vingt ans le pourcentage du chiffre d'affaires à l'exportation de notre Société par rapport à son chiffre d'affaires total est passé de 43 % à un chiffre évoluant entre 65 % et 70 % au cours des cinq dernières années.

Ces succès à l'exportation ne sont pas sans raison. Ils s'appuient sur une politique de conception de nos avions et une politique industrielle développées par Monsieur Marcel DASSAULT depuis plus de 40 ans, poursuivies avec continuité et persévérance, et ayant pour effet d'assurer un développement et une mise au point ultrarapides suivis d'une industrialisation dans des délais extrêmement réduits, tout en assurant une haute qualité de chacun de nos produits.

Faut-il rappeler que 90 prototypes ont précédé nos deux derniers nés le FALCON 900 et le RAFALE dont vous pouvez apercevoir les lignes racées et élégantes sur la planche n° 4.

Aussi ne faut-il pas s'étonner si les deux piliers sur lesquels repose la maîtrise des coûts dans la Société s'appellent :

- une conception réussie et
- un état d'esprit.

Mais pourquoi la Maîtrise des Coûts ? Est-ce la tentation de céder à une mode ou une réalité ?

Au fil des ans, et génération après génération, les avions d'armes ont évolué :

- de la cellule "pilotée" dans tous les sens du terme, soumise aux sensations et à la seule volonté du Maître à Bord,

- à une plate-forme dont les performances statiques, mais surtout dynamiques, pouvaient surpasser les capacités de réaction de son pilote s'il n'était pas assisté d'aides au pilotage, à la navigation et à la conduite de tir ; tous systèmes d'autant plus à la pointe de l'efficacité, qu'il sont riches d'électronique, d'automatismes, et de logiciels.

En termes d'emploi opérationnel, un avion de la fin du vingtième siècle n'est plus comparable à ceux qui l'avaient précédé cinquante ans plus tôt ; leurs coûts non plus. Cette évolution de l'OURAGAN au RAFALE est illustrée sur la planche n° 5.

La nécessité de maîtriser les coûts de développements, de production en série, et d'utilisation en service opérationnel, est donc bien une réalité d'aujourd'hui venue s'ajouter à la longue maîtrise de la qualité et des délais qui ont fait la force et la réputation de notre Société.

Nous y étions tout préparé.

2 - UNE CONCEPTION REUSSIE

La Maîtrise des Coûts c'est avant tout une conception réussie, car c'est à ce stade que se fige environ 80 % du coût futur de sa production en série et de ses conditions de mise en service dans les différentes Armées de l'Air, ou auprès de nos Clients d'avions civils.

C'est ce qui figure sur la planche n° 6.

On comprend ainsi pourquoi les AMD-BA se sont toujours donnés les moyens d'études en Ingénieurs et en puissance informatique pour être en avance sur leur temps.

Cet effort constant en matière de recherche et de développement est schématisé sur les deux planches n° 7 et n° 8, nos efforts ayant porté de manière constante, depuis plusieurs décennies sur :

- les calculs d'aérodynamique théorique tridimensionnelle,
- les calculs de structure en statique et dynamique, conduisant à une réduction importante des programmes d'essais au sol,
- les aides informatiques à la conception, en bidimensionnel, puis en tridimensionnel grâce au programme CATIA développé à l'origine dans notre Société, et placé depuis plusieurs années sous la responsabilité de DASSAULT SYSTEMES, sa filiale,
- l'étude permanente des nouveaux matériaux et des procédés à mettre en oeuvre, avec pour objectif constant de réduire simultanément le poids de nos cellules et leur coût de réalisation,
- le développement des commandes de vol électriques et du contrôle de vol généralisé avec extension de la numérisation des équipements, conduisant à une augmentation importante des performances tant en matière de manoeuvrabilité que de basses vitesses,
- l'application de nouveaux concepts de dialogue homme/machine, organisés autour d'un poste pilote monoplace, lui-même optimisé pour la protection physiologique du pilote sous facteur de charge,
- l'intégration des demandes de signatures réduites dans la conception aérodynamique, le choix des matériaux et la définition des contremesures,
- le développement des études opérationnelles dès le stade de la conception avec simulation et optimisation des missions,
- l'utilisation de l'intelligence artificielle notamment en temps qu'outil d'étude de l'ensemble des équipements et des conditions d'aménagement des cellules afin de minimiser le coût en utilisation opérationnelle future.

L'effort consenti par notre Société en matière d'études et de développement est concrétisé sur les deux planches n°s 9 et 10. Sur une moyenne triannuelle, entre les deux périodes 1980-1982 d'une part et 1983-1985 d'autre part, on peut voir que :

- la part des études et du développement consentie par notre Société par rapport à son chiffre d'affaire, est passée de 11,2 % à 14,58 %,
- et dans les mêmes conditions que la part d'autofinancement est passée de 53,27 % à 57,72 %.

A cette capacité de développement, DASSAULT-BREGUET a toujours su allier la souplesse d'une organisation basée sur la concertation et la rapidité de décision, génératrices de gains en performances, en temps et en budgets.

Dès le stade de conception, sont réunies des équipes pluridisciplinaires regroupant les responsables des études, de la production, de l'assurance qualité et des achats. C'est le stade des équipes intégrées.

Ce travail d'équipe, dès le lancement d'un nouveau programme, et plus particulièrement dans le cas de l'Avion de Combat Européen - ACE RAFALE - est d'autant plus indispensable qu'il doit permettre au mieux l'intégration des sauts technologiques des avions de la nouvelle génération.

Ce travail est d'autant plus efficace qu'il s'appuie sur une capacité sans cesse accrue d'itérations, axées sur des bases de données techniques communes à la disposition de tous les spécialistes du Bureau d'Etudes et de la Production.

En effet, dans le temps passé, les principales disciplines, comme l'aérodynamique, la structure, la propulsion, les circuits avion, etc... étaient traitées de façon relativement indépendante en effectuant pour chacune d'entre elles des analyses de plus en plus détaillées et de nombreux calculs.

Cette méthode, la seule possible à l'époque, a pu donner des résultats satisfaisants tant que les interactions entre ces disciplines restaient limitées du fait de la relative simplicité des avions.

Avec les avions modernes, appelés à répondre à des objectifs opérationnels de plus en plus ambitieux, ces interactions ont une forte tendance à augmenter, afin d'optimiser le produit final.

La planche n° 11, outre la démonstration qu'elle donne de l'évolution régulière et extrêmement importante des moyens informatiques mis à la disposition des ingénieurs de recherche et de développement, avec un facteur de multiplication de 1000 en quinze ans, montre également le développement explosif ainsi offert aux ingénieurs en matière d'itérations et d'optimisations interactives par ordinateurs interposés.

3 - LES EQUIPES INTEGREES

Dans le cas de l'Avion de Combat Européen RAFALE, le travail des équipes intégrées pendant de nombreux mois a permis de déterminer au coût le plus faible (planche n° 12) :

- la structure générale de la cellule,
- les matériaux à retenir, zone par zone,
- les conditions d'aménagement,
- et les essais technologiques permettant de confirmer au plus tôt, les principes de conception des moins onéreux.

Afin d'assurer la cohérence des systèmes et des équipements, leur intégration au meilleur coût dans la cellule et l'élimination des redondances inutiles, le travail sous forme d'équipes intégrées se poursuit avec les principaux équipementiers.

Pour illustrer le travail de l'équipe intégrée qui s'est penchée sur la structure de la cellule du futur ACE RAFALE, nous prenons deux exemples significatifs.

Le premier cas que nous allons illustrer concerne un des tronçons du fuselage (planche n° 13) contenant, principalement, les zones de réservoirs combustible.

Afin d'assurer une fabrication en série, avec un maximum de sous-ensembles, dans le double but de :

- faciliter, dès la conception de la cellule, les possibilités futures de travaux partagés et notamment en coopération européenne,
- permettre une accessibilité plus grande lors des travaux d'assemblage et par voie de conséquence, une réduction des temps de fabrication et des cycles de production,

les études qui ont été réalisées conjointement par l'usine responsable de cette section du fuselage, et par le Bureau d'Etudes, avec les avis permanents de l'Assurance de la Qualité, ont conduit à adopter une solution de structure interne différente de celle qui avait été adoptée sur le démonstrateur RAFALE.

L'ensemble de ces études, dont les éclatés successifs sont présentés sur les deux planches 14 et 15 ont conduit à un gain de coût de plus de 10 % à géométrie identique.

De même, compte tenu de la décomposition en sous-ensembles, le cycle série est passé d'une structure à l'autre de 41 jours à 28 jours, soit un gain de 30 % sur le cycle d'assemblage (planche 16).

Le deuxième exemple que nous prendrons concerne la structure des canards.

A partir de la solution qui vole sur le démonstrateur RAFALE et dont la structure est composée d'un caisson central avec revêtements en carbone sur sous-structure métallique, d'un bord de fuite en carbone, et d'un bord d'attaque en alliage léger (planche 17), deux autres solutions ont été imaginées :

- une solution intégralement en formage superplastique titane et soudure par diffusion avec pivots incorporés soudés par faisceau d'électrons (planche 18),
- une solution mixte dont le bord de fuite reste en matériaux composites et dont l'ensemble caisson + bord d'attaque est réalisé en solution SPFDB titane toujours avec pivots intégrés soudés par faisceau d'électrons (planche 19).

La dernière solution présente le maximum d'avantages techniques (planche 20) pour un coût de réalisation qui globalement sera de l'ordre de 30 % inférieur au coût de la version d'origine. De la même manière, le cycle total de réalisation du canard devrait se trouver être considérablement réduit.

Ces deux exemples illustrent la diversité des solutions qui peuvent être étudiées suivant la nature des structures.

Dans le premier cas nous avons eu le résultat des études qui ont pu être effectuées à matériau identique ; même si en passant de l'avion démonstrateur RAFALE aux futurs avions de série les progrès réalisés depuis le 1er vol du démonstrateur, nous autorisent à intégrer au niveau des fabrications en alliages légers un maximum d'aluminium-lithium.

Le deuxième exemple porte sur un type de comparaisons qui peuvent être faites entre des structures faisant appel à des technologies différentes, pour lesquelles le coût des matériaux et les moyens nécessaires pour leur mise en oeuvre peuvent être très variables suivant les solutions adoptées.

4 - CATIA

A la phase de conception pure, succède la phase de développement avec la réalisation des plans et le lancement des avions de présérie. C'est là que le logiciel CATIA de C.A.O/C.F.A.O. prend toute sa valeur.

CATIA, c'est la possibilité d'enchaîne sans perte de temps, sans duplication de travaux et en parfaite cohérence toutes les tâches :

- de définition : cellule, aménagement, équipements,
- industrialisation : tracés, outillages d'interchangeabilité, outillages de pièces primaires touchant à la forme, outillages d'assemblage,
- de fabrication : adaptation des "modèles CATIA" aux besoins de la production, programmation C.N. pour les machines de production et de contrôle, réalisation des logiciels de traitement pour automatisation des essais (câblages électriques, systèmes),

en partant d'une base de données unique, constamment mise à jour dans le cadre du programme des "modèles CATIA", et liée à l'autre base de données complémentaires, constituée par les nomenclatures et les données permanentes de production.

Le schéma d'utilisation de CATIA est représenté sur la planche n° 21.

Des sources uniques d'information rigoureusement gérées, des équipes pluridisciplinaires légères mais très interactives, un enchaînement des tâches de la Conception à la Production série évitant les répétitions, les reprises, les transformations de données, les duplications d'efforts, minimisant les investissements en études et industrialisation, forment les conditions nécessaires pour allier à une définition réussie un coût de conception et de développement maîtrisé.

Il y a près de vingt ans un certain rapport rédigé par la RAND CORPORATION, commandité par l'U.S. Air Force, avait fait grand bruit à l'époque dans le monde de l'aéronautique. Quel était donc le miracle qui donnait aux AMD-BA une efficacité à nul autre pareil ? La réponse demeure toujours la même : une intégration harmonieuse de la technique et des hommes.

Le schéma de l'ensemble de ces articulations est donné sur la planche n° 22 où se trouvent connectés autour de la symbolisation de l'Equipe Intégrée ses principaux participants, les fichiers uniques et le résultat de leur travail :

. Une conception réussie
. Une maîtrise des coûts en production et en service.

5 - REDUCTION DES COUTS EN SERIE

Arrive la phase de production en série. La définition de la cellule, de ses équipements et de l'ensemble des systèmes est acquise. Les prévisions de performances, tant en aérodynamique, qualité de vol, que conduite du système d'armes ont été confirmées à l'aide du nombre minimum d'avions de développement, et de vols d'essais dont les résultats obtenus en temps réel sont rapidement comparés aux données d'origine, poursuivant à ce stade les itérations très fréquentes entre théorie et résultats.

En production série la maîtrise des coûts doit s'entendre en tant que réduction permanente des coûts de fabrication et cette réduction permanente passe par :

. la maîtrise des flux
. la gestion de la qualité
et un
. état d'esprit.

Nous ne nous étendrons pas sur la maîtrise des flux qui n'est pas le sujet principal de cet exposé. Nous ne retiendrons que l'objectif qui doit être présent dans toutes les actions développées au niveau des bases de données (nomenclatures) et de leur exploitation, l'objectif : <u>Zéro manquant</u>.

La diminution des surcoûts et la gestion de la qualité sont intimement liées.

L'objectif à atteindre : Zéro défaut, pour ambitieux qu'il soit dans notre branche professionnelle, parcourue sans cesse par les remous de versions successives et d'adaptations permanentes des moyens aux variations des cadences de fabrication, doit cependant être considéré par toute la hiérarchie et tout le personnel d'exécution comme une asymptote à portée de toutes les volontés.

Pour cristalliser cette volonté plusieurs voies sont utilisées simultanément et sont schématisées sur la planche n° 23 :

. la saisie et l'analyse des "surcoûts",

. la mesure de la qualité et son exploitation par les niveaux hiérarchiques appropriés,

. la sensibilisation de tous les "acteurs de la qualité" aux problèmes de la qualité et des coûts,

. la mise en place de structures opérationnelles et fonctionnelles afin que soient :

- supprimées les barrières inter-services
- accélérée la résolution des problèmes
- facilité le développement de la créativité.

Cette planche nécessiterait à elle seule un long développement, tant il est difficile en quelques phrases clés de faire passer le message de la gestion participative, dans le plein sens de son expression.

Nous nous contenterons, afin de ne pas allonger cet exposé, de donner deux exemples issus de son application :

Premier exemple (planche 24) : variation de l'Indice général de la qualité pour une famille avion de 1976 (date de création des indices qualité) à 1982 (Nota : plus l'indice est faible, plus la qualité est grande), et une autre famille avion de 1984 à 1986.

Deuxième exemple (planche 25) : nombre de sujets abordés et de sujets résolus concernant la qualité et les surcoûts par les "trinômes" en une année, d'octobre 1985 à octobre 1986, les trinômes étant une des formes d'application des groupes de la Qualité.

Ce qu'il y a de plus remarquable à retenir sur ces deux planches est :

- pour la première, l'effet de rémanence positif résultant des efforts d'organisation mis en place, la "qualité" ayant été beaucoup plus rapidement obtenue sur la deuxième famille que sur la première (rang 40 au lieu de rang 400),
- pour la deuxième, le rapport constamment grandissant du nc bre de sujets résolus par rapport au nombre de sujets abordés.

6 - CONCLUSION

La maîtrise des coûts a été, dans les décennies passées, une situation de fait, comme la prose, se pratiquant sans le dire et concrétisée par des années d'expérience accumulées qui s'appellent :

Demandes/Réponses entre Bureaux d'Etudes et Usines

Amélioration des Méthodes de Fabrication

Réduction des Coûts Usines

Recherche d'Investissements Rentables

Participation du personnel aux Suggestions Valables.

L'évolution des techniques, la sophistication de plus en plus poussée des cellules et des équipements, les difficultés économiques qui se sont étendues depuis, à la plupart des Nations nous ont conduit, depuis une dizaine d'années, à formaliser de plus en plus la motivation du personnel, les moyens et les structures, faisant de la maîtrise des coûts le troisième pilier qui ajouté aux deux piliers traditionnels de la conception et de la rapidité d'exécution, forment l'assise sur laquelle reposent notre force et notre volonté de gagner les paris de l'an 2000.

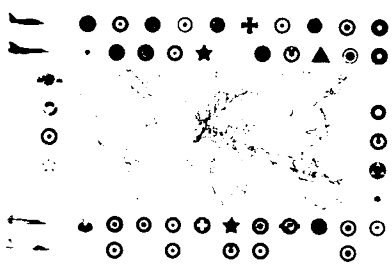

FIG. 1 - MIRAGE AND ALPHA JET IN THE WORLD

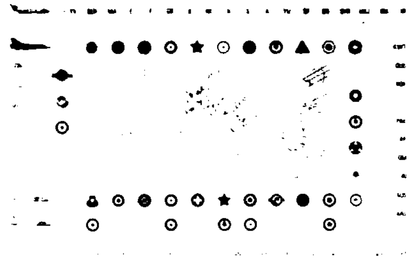

FIG. 2 - MYSTERE AND MIRAGE IN THE WORLD

FIG. 3 - TURNOVER EXPORT RATIO

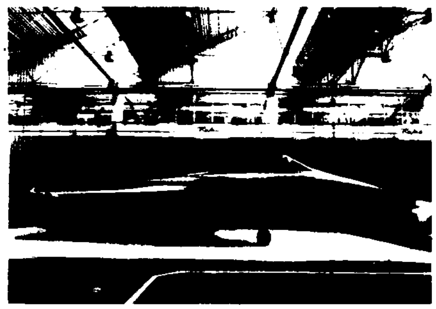

FIG. 4 - RAFALE DEMONSTRATOR

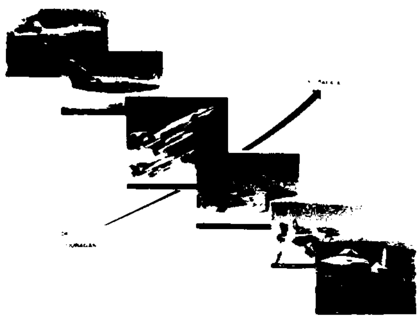

FIG. 5 - FROM OURAGAN TO RAFALE

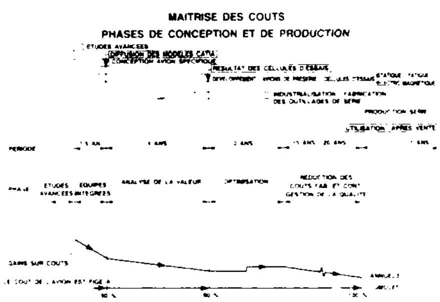

FIG. 6 - COST CONTROL

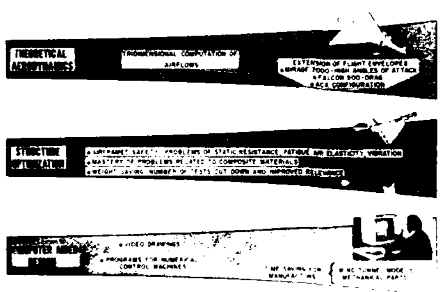

FIG. 7 UTILIZATION OF MODERN COMPUTATION PROCESSES

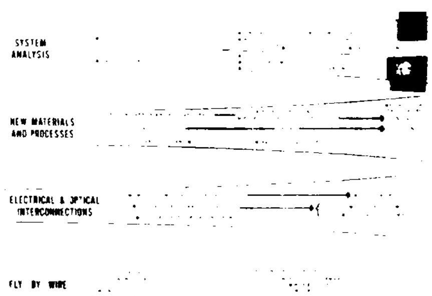

FIG. 8 - OPERATIONAL ANALYSES AND ADVANCED TECHNOLOGIES

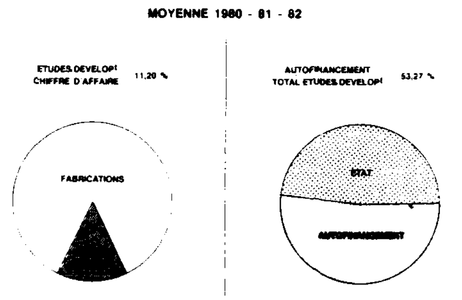

FIG. 9 - R & D EFFORT (80-81-82)

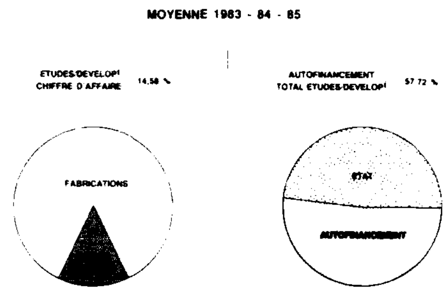

FIG. 10 - R & D EFFORT (83-84-85)

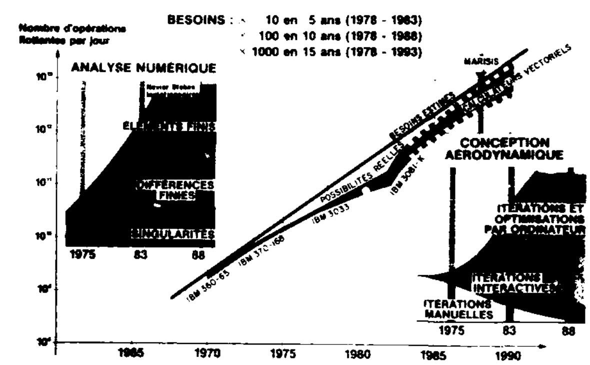

FIG. 11 - COMPUTERS AND COMPUTATIONAL FLUID DYNAMICS

LEADER :	VICE PRESIDENT MANUFACTURING IN CHARGE OF PRODUCTIVITY
PARTICIPANTS	DESIGN OFFICE QUALITY CONTROL MANUFACTURING FACILITIES
ACTIVITY	• AIRFRAME STRUCTURE DESIGN → MANUFACTURE BREAKDOWN FOR LOW COST - LOW CYCLE - PRODUCTION • MATERIALS SELECTION • SYSTEMS INSTALLATION AT MINIMUM COST • TECHNOLOGY TESTS IN ORDER TO CONFIRM THE PRINCIPLES LEADING TO THE LOWEST COSTS

FIG. 12 - INTEGRATED TEAM

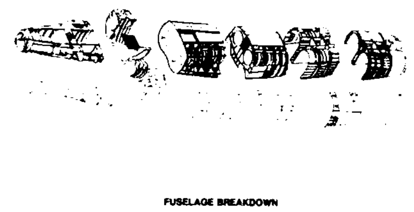

FIG. 13 - ACE/RAFALE - FUSELAGE BREAKDOWN

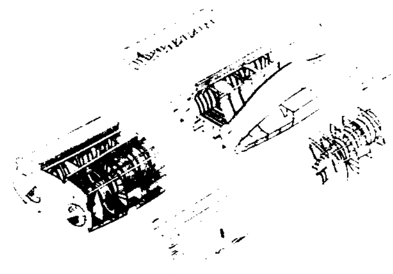

FIG. 14 - ACX/RAFALE DEMONSTRATOR - T3 BREAKDOWN

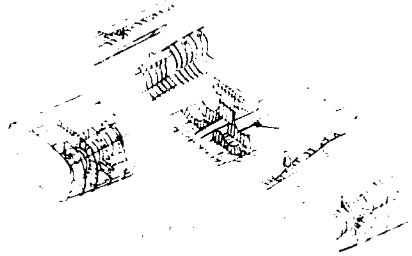

FIG. 15 - ACE/RAFALE - T3 BREAKDOWN

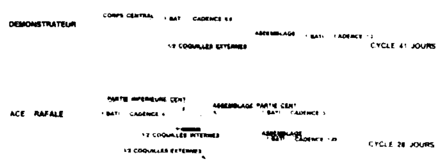

FIG. 16 - T3 SECTION CYCLE COMPARISON

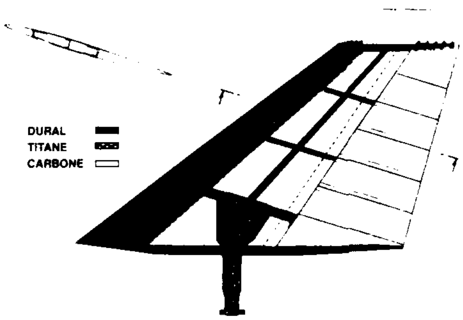

FIG. 17 - ACX/RAFALE DEMONSTRATOR - FOREPLANE (CARBON)

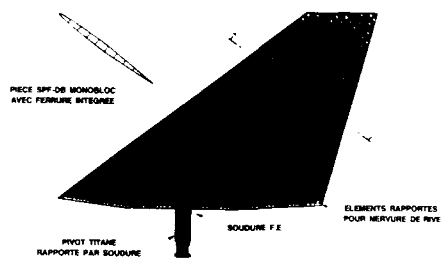

FIG. 18 - ACE/RAFALE - FOREPLANE (SPF-DB)

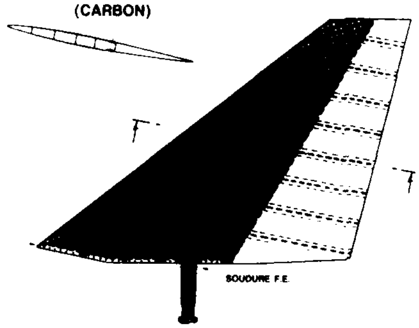

FIG. 19 - ACE/RAFALE - FOREPLANE (SPF-DB + CARBON T.E.)

	TOUT SPF-DB	SPF-DB - B.F CARBONE	CARBONE
MASSES	44 kg	43 kg	46 kg
INERTIES	2.8 kg m²	2.2 kg m²	3.0 kg m²

FIG. 20 - ACE/RAFALE - FOREPLANE COMPARISON

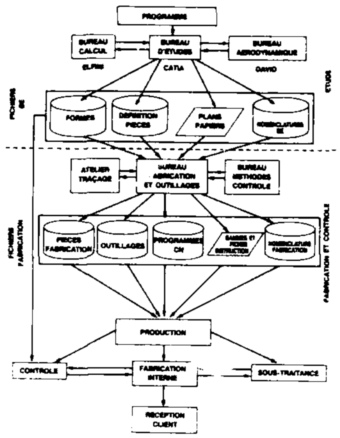

FIG. 21 - CAD/CAM EXCHANGES

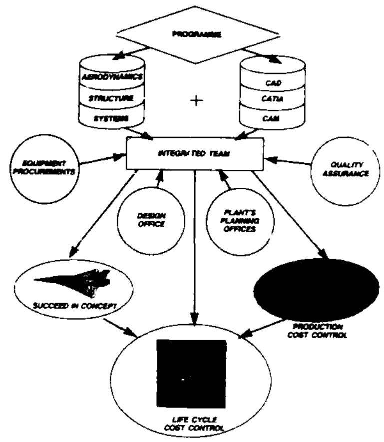

FIG. 22 - COST CONTROL ARCHITECTURE

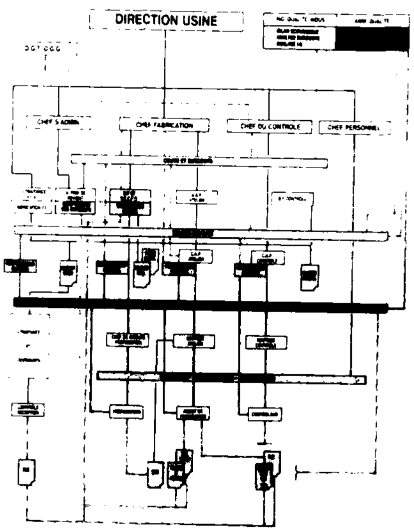

FIG. 23 - QUALITY GESTION

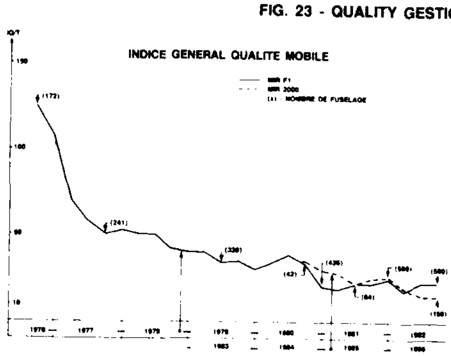

FIG. 24 - QUALITY RATIO

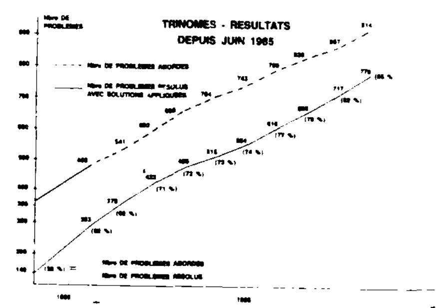

FIG. 25 - TRINOMS - RESULTS

ACCELERATION OF PROTOTYPE DEVELOPMENT AND REDUCTION OF COST BY MULTIDISCIPLINARY INTEGRATION

by

J.Y. LAZARD, DEPUTY VICE-PRESIDENT, PRODUCTION
AVIONS MARCEL DASSAULT-BREGUET AVIATION

SUMMARY.

Since its creation AMD/BA has built 92 prototype aircraft, the last being the RAFALE, a new technology demonstrator, forerunner of the future combat aircraft. The industrial policy of the company, pursued with continuity and perseverance, has always involved a very fast development, followed by a rapid industrialization and the realization of high quality products.

However, with the ever increasing complexity of modern aircraft, maintaining this orientation has required an adequate new organization and the development of several unique technical tools.

I - EXPERIENCE -

For more than 40 years, the image of AVIONS MARCEL DASSAULT-BREGUET AVIATION has been built on high quality production of military aircraft and business jets.

Without giving too many details, it appears useful to describe shortly what the company represents.

During these last 40 years AMD/BA have produced about 6000 military and civil aircraft and exported a large part of their production to 60 countries. This production covers a large family of business jets and military aircraft, the latter including air-defense, ground attack and trainer versions, carrier-based aircraft, supersonic penetration bombers and several types of multirole fighters.

The first two figures indicate the extent of our world exports for the MYSTERE, MIRAGE and ALPHA JET family.

Their volume is shown on figure 3, indicating that in average the % of export turnover increased in 20 years from 43 % to about 65 to 70 % in the last 5 years.

It is pointed out that this success in exports was mainly due to the application of an industrial policy initiated by M. Marcel DASSAULT more than 40 years ago, pursued with continuity and perseverance, with the objective to associate with a fast prototype development a rapid industrialization and a high quality of the resulting products.

90 prototypes preceded the last two, the FALCON 900 and the RAFALE technology demonstrator illustrated on figure 4.

As a result of this policy, it is not surprising that the two basic pillars, helping to master the cost-effect in the company, are :

- a successful design concept, associated with
- a dedicated attitude.

But why cost-control ? Is it a new fashion or a reality ?

During the last decades combat aircraft have evolved :

- from a piloted airframe, submitted more or less completely to the pilot action
- to a high performance complex platform which would significantly overpass the pilot reaction capabilities without the aid of sophisticated flight control, navigation and fire control systems with their efficiency enhanced by electronics, automation, on-board software, etc...

In operational terms, an aircraft at the end of the 20th century will be fundamentally different from the previous 50 years old generation ; and also in terms of cost. This huge evolution from the OURAGAN to RAFALE is illustrated on figure 5.

The need to master the ever increasing development, production and operational cost, i.e. the life cycle cost, becomes therefore today's reality to be added to the other usual performances of our company, i.e. efficient quality and schedule control.

Our company was well prepared to this new task.

2 - A SUCCESSFUL DESIGN CONCEPT -

Mastering of the cost means at the very first a successful design concept. It is at this early conceptual stage that about 80 % of the life cycle cost of the future military or civil product is being cristallized.

This basic fact is shown on figure 6.

This is the reason why AMD/BA have always endeavoured to have strong design teams and advanced powerful design tools.

The R & D effort of AMD/BA is illustrated on figures 7 and 8, concerning :

- tridimensional computational fluid dynamics
- static and dynamic structural optimisation, allowing a significant reduction of ground testing
- computer aided design, initially two-dimensional, followed by the in-house developed tridimensional CATIA software, presently under the responsability of our subsidiary company, DASSAULT SYSTEMES
- new materials and fabrication processes with the continuous objective of simultaneous weight and cost reduction
- development of fly-by-wire controls and CCV's and digital equipments, enhancing aircraft maneuverability and high angle of attack behaviour
- new man-machine concepts in an optimised single seater cockpit station for the physiological pilot protection against high load factors
- integration of low observability requirements with the aerodynamic concept, material selection and ECM
- operational research studies with mission simulation and optimisation at the conceptual design stage
- use of artificial intelligence engineering as a design tool for equipment and airframe layout, in view of operational cost reduction.

The financial effort invested in design and development is presented on figures 9 and 10. It is shown that between 1980-1982 and 1983-1985 the triannual investment average increased :

- from 11.2 % to 14.58 % of the turnover for design and development
- from 53.27 % to 57.72 % for the autofinancing.

Design and development capability has always been associated with a flexible organisation, based on large consensus and on short response time which are definitely sources of time and cost saving.

At the early conceptual stage a multidisciplinary team is formed regrouping the design, production, quality assurance and procurement personnel, constituting the integrated team.

At the program initiation and particularly for the European Combat Aircraft - ACE RAFALE - such an integrated team is an absolute necessity to incorporate in the best conditions the numerous technological jumps in the new generation aircraft.

This work environment efficiency is significantly improved by an ever increasing fast iteration capability, using a unique common technical data base, available to all design and production specialists.

This methodology is very different from the past, when the principal disciplines as aerodynamics, structures, propulsion, aircraft circuits, etc... were dealt with relatively independently and more and more detailed analysis was carried out successively within each individual discipline.

This method, the only possible at that time, was able to give satisfactory results as long as the interactions between disciplines were limited due to the relative simplicity of the aircraft.

With modern aircraft incorporating more and more ambitious operational objectives, these interactions are becoming significantly stronger in order to optimise the final product.

Figure 11, in addition to showing the regular and very large evolution of computational means available for design and development with an amplification factor of 1000 in 15 years, also indicates the explosive development in the area of interactive iterations and optimisations.

3 - INTEGRATED TEAMS -

The integrated teams of the RAFALE program working during several months have defined on a minimal weight and cost basis (figure 12) :

- the general structure of the airframe
- the materials
- the general aircraft layout
- the technological tests to confirm as rapidly as possible the lowest cost solution.

In addition, in order to ensure system and equipment coherence and their integration in the airframe at minimal cost, and to eliminate unnecessary redundancies, the integrated team is working in tight cooperation with the main equipment suppliers.

To illustrate the work made on the future ACE - RAFALE structure, we present two characteristic examples.

The first case concerns a fuselage section (figure 13) containing fuel tanks.

In order to define the production version with a large number of subparts, with the objective to :

- facilitate, right from the initial airframe concept, the future possibilities of work-sharing, in particular in European cooperation
- allow an increased accessibility during the assembly, and consequently a reduction in manufacturing time and production cycles

the design, performed jointly by the factory responsible for this fuselage section and the Design Office, in continuous consultation of the Quality Assurance, was modified in respect of the internal structure of the RAFALE demonstrator.

The main result, represented in successive fuselage section breakdowns on figures 14 and 15, was a cost saving of more than 10 % for a given geometrical configuration.

In addition, due to this subpart breakdown, the production cycle decreased from 41 days for the demonstrator to 28 days, representing a 30 % gain on the assembly cycle (figure 16).

The second example concerns the canard structure.

From the RAFALE demonstrator structural solution, consisting in a central torsion box with carbon skins on a metallic substructure, a carbon trailing-edge and a light alloy leading-edge (figure 17), two other configurations were derived :

- an entirely SPFDB titanium structure, with incorporated electron beam welded spigots (figure 18)
- a combined solution, with the trailing-edge still in composite material and the torsion box + leading-edge in SPFDB titanium (figure 19).

The last solution is technically the most advantageous (figure 20) with a global manufacturing cost 30 % lower in respect of the original version and the total fabrication cycle considerably reduced.

These two examples illustrate the great variety of design possibilities according to the nature of the structures.

In the first case the results were obtained with identical materials ; it is pointed out in addition, that the advances realised in light alloys in the time interval between the demonstrator and the production version, will allow to incorporate a large quantity of aluminium-lithium in the airframe structure.

The second example highlights another type of comparison made between structures using different manufacturing technologies, where the cost of materials and processing techniques are totally different.

4 - CATIA -

To the pure conceptual phase succeed a development phase and the manufacturing of several preproduction aircraft. This is the phase where the CAD/CAM software CATIA appears particularly useful.

CATIA offers the possibility to undertake without loss of time, without duplication and in perfect coherence the tasks :

- of definition : airframe, circuits installation, equipments
- of industrialization : lofting, interchangeability tooling, primary part and assembly tooling
- of manufacturing : adaptation of "CATIA models" to the production needs, numerical control programming, development of processing software for automated tests (electric wiring, systems) etc...

using a single data base, continually updated in relation with the CATIA models control and connected to the other complementary data base, consisting in parts file and permanent production data.

A bloc diagram, indicating how CATIA is integrated in the production process, is presented on figure 21.

Rigourously managed information sources, light but highly interactive multidisciplinary teams, tasks performed from the concept formulation to mass-production without repetitions and effort duplication, are the conditions required to reach a successful definition and a reduced developmental and operating cost.

20 years ago, a famous RAND CORPORATION report, supported by the U.S. AIR FORCE, raised the question of the reasons of AMD/BA efficiency in the aeronautical world. The answer remains the same : a harmonious integration of techniques and men.

The bloc diagram of figure 22 presents the principal participants around the Integrated Team and the results of their combined work :

. a successful design concept

. a rigourous production and operational cost control.

5 - PRODUCTION COST REDUCTION -

At the production phase, the definition of airframe, equipments and systems is acquired. Aerodynamic performance, flying qualities and weapon-system operating characteristics were established using a minimum number of developmental aircraft and the corresponding flight test results, processed in real-time, compared to the predicted data.

Mastering of cost in production is obtained by :

. the material flow control

. the quality control

and once more

. a dedicated attitude

We will not address on the material flow control, which is not our subject. We will address only the objective which must be present in all actions developed at the level of data base (parts file) and its use, the Zero Missing Objective.

Reduction of overcost and quality control are intimately related.

The Zero Defect Objective, ambitious in our profession submitted to the irregularities of successive versions and to continuously varying production rates, must be however considered as an asymptote by the personnel involved.

With these objectives in mind, several means are used simultaneously as shown on figure 23 :

. registration and analysis of overcosts

. quality measurement and its use at appropriate hierarchical levels

. sensitivity of all "quality players" to the problems of quality and cost

. creation of operational and functional structures in order to

- eliminate inter-service barriers
- accelerate problems resolution
- facilitate creativity development.

This figure alone would need a long development, the message of participative management being very difficult to transmit in a few sentences.

We will limit our presentation to two examples :

- first example (figure 24) : variation of the General Quality Index for an aircraft family from 1976 (creation date of the quality index) to 1982 (Note : the lower the index, the better the quality) and for another family from 1984 to 1986
- second example (figure 25) : number of subjects considered and solved by the trinomes in one year, from October 1985 to October 1986, the trinomes being one application form of the Quality Circles.

The remarkable characteristics of these figures are :

- for the first, the positive remanence effect resulting from the organizational effort, the Quality being reached more rapidly on the second family than on the first (at n° 40 instead of 400)
- for the second, the ever increasing ratio of the number of subjects solved related to the number of subjects considered.

6 - CONCLUSION -

Mastering of the costs was, during the past decades, an existing technique based on cumulated experience, called :

- Questions/Answers between Design Office and Production plants
- Improvement of Manufacturing Techniques
- Factory Cost Reduction proposals
- Research of Profitable Investments
- Personnel Participation to Valid Suggestions.

Technical evolution, the ever increasing sophistication of airframes and equipment, the economic difficulties concerning now most countries, have conducted us in the last 10 years to an increased formalisation of the motivation of the personnel, of the methods and structures, making the mastering of costs the third pillar, which added to the two traditional pillars of successful concept and fast execution, forms the basis of our force and willingness to face the challenges of the year 2000.

ORGANISATION DES ACTIVITES DE DEVELOPPEMENT D'HELICOPTERES EN VUE DE REDUIRE LES COUTS ET LES CYCLES

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1 SOMMAIRE

Au cours de ces dernières années, les coûts et les cycles de développement des hélicoptères ont fortement augmenté par rapport aux coûts de production. En effet, l'accroissement des demandes des spécifications impose de plus en plus d'efforts concernant les performances, les matériaux, les capabilités opérationnelles des appareils et des systèmes qui deviennent de plus en plus sophistiqués.

Pour ces raisons, il est important de réduire les cycles et les coûts des programmes de développement afin de ramener l'ensemble des efforts de développement dans des proportions plus raisonnables.

La recherche d'une telle réduction est obtenue à travers une définition convenable des tâches qui doit être faite au cours d'une phase de prédéveloppement où sont bien précisés les objectifs visés et choisies les performances techniques résultant du meilleur compromis entre les performances à obtenir et les risques techniques en jeu.

Cette phase de prédéveloppement est suivie du programme de développement où la conception, la fabrication et les essais sont profondément imbriqués, en essayant de limiter les risques à chaque étape.

Naturellement, la flexibilité doit être suffisante de façon à maintenir à chaque instant le meilleur compromis entre la conception, le produit fabriqué et les essais.

2 INTRODUCTION

En Février 1955, l'ALOUETTE II effectuait son premier vol ; trente deux ans plus tard, le 6 Février 1987, une nouvelle version du SUPER PUMA équipée d'un rotor principal sphériflex entamait sa phase d'essais en vol.

Il n'est pas besoin d'être un fin technicien pour imaginer la somme de travail qu'il a fallu fournir pour franchir cette étape.

Durant ces trente deux ans, l'industrie française d'hélicoptères a maintenu, comme ses concurrents, un effort constant de développement de produits nouveaux toujours plus performants pour satisfaire une clientèle toujours plus exigente et rester compétitif sur le marché mondial.

La vitesse a plus que doublé pour les machines les plus performantes, les moyens de pilotage rustiques au départ sont devenus quasiment automatiques avec des systèmes à calculateurs numériques, le confort est maintenant équivalent aux autres moyens de transport, la polyvalence de mission a été développée aussi bien dans les domaines civils que militaires, la fiabilité et la sécurité des matériels ont été accrues dans des proportions considérables, le coût d'exploitation a largement diminué.

Toutes ces évolutions deviennent de plus en plus difficiles et nécessitent des efforts de recherches théorique et technologique sans cesse croissants.

Par ailleurs, si les appareils des première et seconde générations, ALOUETTE, SUPER FRELON, GAZELLE, PUMA étaient des programmes financés par l'Etat français, les machines de la troisième génération, ECUREUIL, DAUPHIN, SUPER PUMA ont été développées sur fonds propres avec une aide étatique limitée et d'ailleurs remboursable. Il en sera de même pour la plupart des développements futurs.

Or, l'effondrement du marché civil et militaire,depuis cinq ans, rend plus difficile les investissements.

Pour conserver des activités de développement suffisantes, il est donc vital de s'organiser dans tous les domaines pour combattre et réduire l'augmentation des coûts et des cycles en se dotant de structures, de moyens, de procédures, adaptés pour limiter les risques et faire bien du premier coup.

Pour tenir ces objectifs, la Division Hélicoptères de l'Aérospatiale s'est fixée une méthodologie de conduite de programme en regroupant toutes les activités de développement au sein d'une même direction. Par ailleurs, une organisation par programme permet de centraliser les décisions relatives à un programme donné.

D'autre part, dans chaque secteur, Bureau d'Etudes, Fabrication, Achats, Essais sol et vol, des dispositions ont été prises pour réduire de façon significative les cycles et les coûts aussi bien pour le développement que pour l'industrialisation.

Elle a adopté enfin une politique de développements préliminaires, dits exploratoires, dans les domaines où l'innovation est importante et présente, de ce fait, un risque élevé.

3 LES ACTIVITES DE DEVELOPPEMENT SONT VITALES

Le niveau des activités de développement est le baromètre de la vitalité d'une industrie de haute technologie telle que celle des hélicoptères.

Or, on note aujourd'hui une pression de l'accélération du progrès technologique à tous les échelons du monde industriel.

Pour vendre, il faut s'adapter au marché, ou le créer, mais ne plus attendre que le client vienne à soi.

Pour vendre, il faut aussi envisager de plus en plus des compensations ou des coopérations, donc céder du savoir faire tout en conservant une avance technologique.

Plus encore que par le passé, l'anticipation technologique est une nécessité absolue pour :

- Rester compétitif
- Avoir des possibilités de transferts technologiques avec des risques limités.

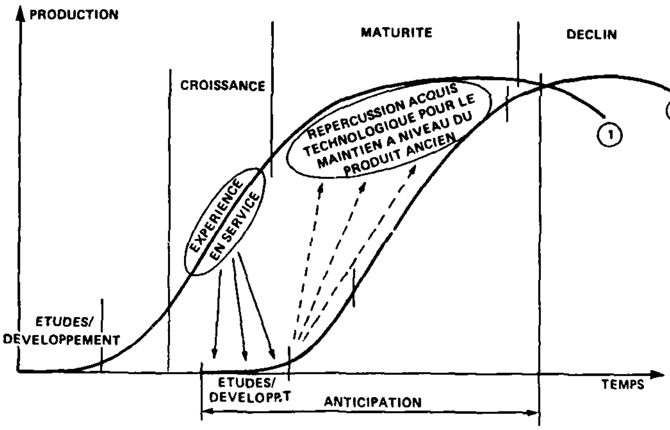

Figure 1 : INTERDEPENDANCE DES PRODUITS ET ANTICIPATION

La Figure 1 montre que pour maintenir une présence sur le marché, il faut anticiper les nouveaux développements de façon à disposer des produits de remplacement pour compenser le déclin des produits anciens. On note également que l'anticipation permet de faire bénéficier le produit existant des retombées technologiques du futur, donc de prolonger sa présence sur le marché et d'accroître la rentabilité industrielle.

Jusqu'à présent, la Division Hélicoptères de l'Aérospatiale a su anticiper pour être présente au bon moment comme le témoigne la gamme d'appareils développés depuis plus de trente ans.

Pour conserver cette présence, il est absolument indispensable de ramener les coûts de développement à des niveaux supportables et de limiter les temps nécessaires de façon à s'adapter rapidement à la demande du marché.

Il faut également se doter de moyens et de structures permettant de contrôler à tout instant les résultats par rapport aux objectifs, mais suffisamment souples pour ne pas bloquer la créativité.

4 EVOLUTION DES COUTS DE DEVELOPPEMENT A LA DIVISION HELICOPTERES AEROSPATIALE

Le coût de lancement d'un produit nouveau se décompose en frais de développement et frais d'industrialisation. Une partie de ces frais fixes, fonction des quantités lancées, ajoutée au coût de production donne le prix de revient initial. Le prix de revient final est ensuite obtenu en ajoutant les coûts indirects et les coûts complémentaires.

L'objectif étant en fait d'obtenir un prix de revient le plus bas possible, et compte-tenu que les coûts complémentaires et indirects sont fixes, l'effort de réduction doit être porté à la fois sur le coût de production et les dépenses générales.

Or, en règle générale, la réduction du coût de production entraine une augmentation des dépenses générales, donc de l'amortissement qui peut annuler l'effet recherché.

Le compromis coût de production - dépenses générales est donc un choix difficile lié aux conditions de lancement du produit.

La phase de développement est la plus importante car c'est au cours de cette première étape que se construit le produit aussi bien sur le plan technique qu'économique, et il serait très dangereux de sacrifier la qualité du développement pour réduire les coûts.

La Figure 2 montre que, pour les appareils de la dernière génération, les dépenses de développement et d'industrialisation ont été sensiblement équivalentes en proportion.

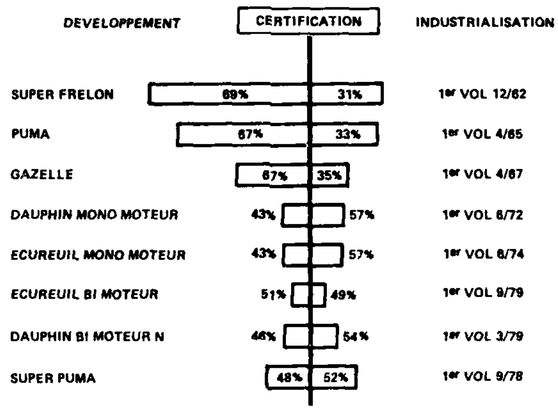

Figure 2 : REPARTITION DEPENSES DEVELOPPEMENT ET INDUSTRIALISATION

Par dépenses de développement d'un programme, il faut entendre :

- Les travaux de recherche et de prédéveloppement
- Les maquettes
- Les études et dessins prototypes
- Les développements d'équipements spéciaux
- Les essais sol en laboratoire ou soufflerie
- La fabrication de un ou plusieurs prototypes
- Les essais vol des prototypes jusqu'à la certification.

La Figure 3 donne le rapport des coûts de développement, en francs constants 1985, de notre gamme par rapport à celui de l'ALOUETTE II pris comme référence.

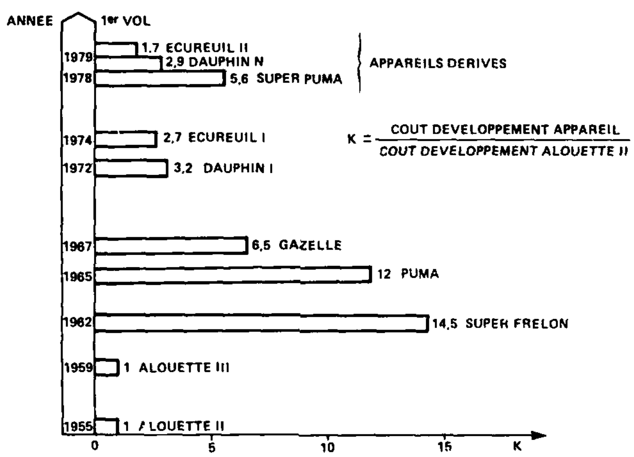

Figure 3 : EVOLUTION DES COUTS DE DEVELOPPEMENT – REFERENCE ALOUETTE II

On remarque une augmentation importante des coûts de développement des appareils de la deuxième génération des années 1960 - 1970 avec une brusque diminution pour les appareils de la troisième génération des années 1970 - 1980.

La Figure 4 suivante, plus représentative de cette évolution, indique le coût de développement, en francs constants 1985, du kilogramme de masse totale ramené à celui de l'ALOUETTE II. La masse totale est la masse revendiquée à la première certification.

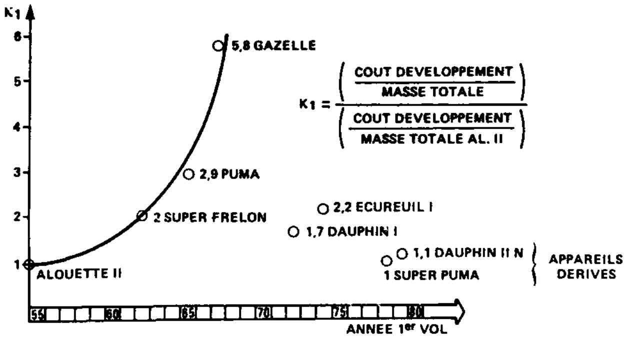

Figure 4 : EVOLUTION DES COUTS DE DEVELOPPEMENT PAR kg DE MASSE TOTALE

On voit que les coûts de développement par kg des appareils de la seconde génération ont fortement progressé jusqu'à atteindre un rapport de 6 pour la GAZELLE vis-à-vis de l'ALOUETTE II. Ceci s'explique en grande partie par le bond technologique avec une accumulation importante de risques. La GAZELLE est un appareil léger très performant avec énormément d'innovations technologiques pour l'époque, moyeu rotor principal semi-rigide, pales principales composites, rotor arrière fenestron, atterrisseur basse fréquence, structure principale sandwich très légère, dont la mise au point a été longue et coûteuse. Le nombre d'appareils de développement était aussi élevé.

Pour casser cette inflation, l'Aérospatiale a décidé en 1970 de modifier ses méthodes de développement en créant des ilôts opérationnels regroupant tous les techniciens concernés par le développement d'un même produit sous l'autorité d'un Chef de Projet.

Le DAUPHIN I a été le premier appareil à bénéficier de cette nouvelle organisation. D'autre part, les techniques développées sur GAZELLE ont été reconduites sans innovation particulière. Des risques techniques limités et une organisation permettant de bien maitriser le programme ont permis de réduire de façon très significative le coût de développement.

Par contre, pour l'ECUREUIL I, deuxième appareil à être développé en organisation ilôt, on note de nouveau une tendance à l'accroissement du coût de développement.

Cet appareil léger, destiné à une large diffusion sur le marché civil, a été lancé avec un coût de production objectif 3 fois inférieur à celui de l'ALOUETTE II. A partir d'études d'analyse de la valeur, la conception a été plusieurs fois remise en cause pour atteindre le devis cible, parfois avec des innovations technologiques importantes comme le moyeu rotor starflex en matériaux composites.

L'Aérospatiale a volontairement accepté d'augmenter les coûts de développement, sur cet appareil de grande diffusion, pour arriver au coût objectif dans la mesure où les études de marchés permettaient d'amortir sur une grande quantité. Plus de 1500 ECUREUIL I et II sont fabriqués à ce jour depuis Septembre 1977, date de la première certification.

Les coûts de développement du SUPER PUMA et du DAUPHIN II N, dérivés d'appareils existants, ne peuvent pas être comparés directement aux autres machines qui étaient, elles, entièrement nouvelles.

Trois conclusions se dégagent de cette analyse. D'une part, une organisation bien adaptée aux activités de développement permet de mieux maitriser les coûts. D'autre part, le cumul d'innovations technologiques sur un même appareil coûte très cher en mise au point. Enfin, une synergie interprogramme permet des économies substantielles.

Ces réflexions ont conduit l'Aérospatiale à modifier sa politique de développement et à se doter de structures et de méthodes encore mieux adaptées.

Par ailleurs, des réflexions au sein de groupes de qualité ont conduit à des propositions de réductions de coût et de cycle significatives tout en améliorant la qualité.

5 EVOLUTION DES CYCLES DE DEVELOPPEMENT A LA DIVISION HELICOPTERES AEROSPATIALE

Pour réduire les coûts, pour pouvoir s'adapter à l'évolution du marché, pour conserver une quantité d'innovations suffisante, il faut effectuer toutes les activités de développement dans un temps le plus court possible, après avoir cependant réfléchi suffisamment au bon choix des solutions technologiques retenues.

Sur la Figure 5, on peut voir que les cycles de développement des appareils Aérospatiale ont suivi une évolution semblable à celle des coûts.

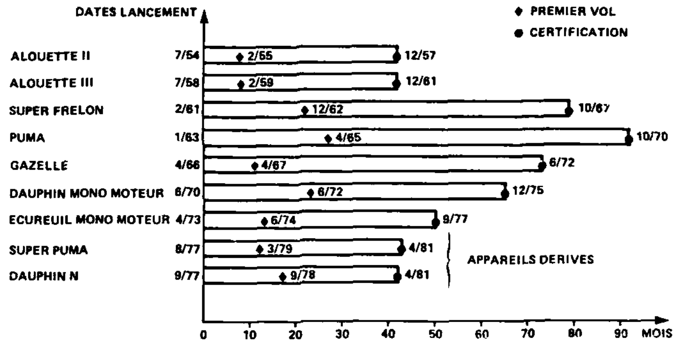

Figure 5 : CYCLES DE DEVELOPPEMENT

On remarque que l'ECUREUIL I a été développé en 50 mois contre 42 pour l'ALOUETTE II.

Il apparaît par ailleurs que 70 % environ du cycle est en moyenne consacré à la mise au point à partir du premier vol jusqu'à la qualification.

Comme dans le domaine des coûts, l'Aérospatiale a entrepris une campagne énergique de réduction de cycles dans tous les secteurs du développement. Nous verrons que des résultats importants ont déjà été obtenus.

6 MESURES PRISES RECEMMENT AU SEIN DE LA DIVISION HELICOPTERES POUR REDUIRE LES COUTS ET LES CYCLES – RESULTATS OBTENUS

Le déroulement d'un programme peut être assimilé à une descente de skis relais.

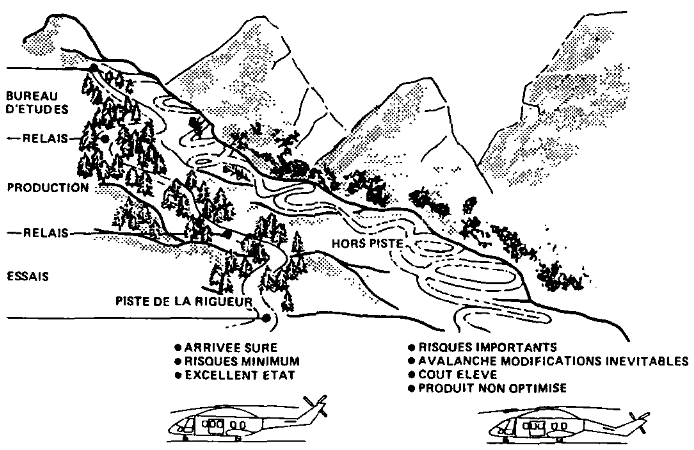

Figure 6 : LA CONDUITE DE PROGRAMME

Si au départ le Bureau d'Etudes prend la bonne piste, le passage du relais avec la Production, puis entre la Production et les Essais se fera dans de bonnes conditions.

Dans le cas contraire, si le Bureau d'Etudes s'oriente au départ hors piste, il y a une forte probabilité pour qu'il déclenche une avalanche de modifications qui par effet boule de neige, conduira à une majoration importante des coûts et des temps et à un produit mal optimisé.

L'Aérospatiale s'est dotée d'une politique, d'une méthodologie et d'une organisation de conduite de programme de développement propres à choisir les pistes les plus sures.

Ensuite, tout au long du trajet, des mesures de réductions de coût et de cycles ont été prises tout en recherchant une amélioration de la qualité.

6.1 Politique de développement

Les expériences passées ont montré que le cumul d'innovations technologiques sur un même produit en développement coûte très cher.

Aujourd'hui, l'Aérospatiale préfère conduire des développements parallèles sous forme de développements exploratoires ou développements techniques probatoires dans les domaines à risque élevé dans le cadre d'une politique de produits.

Ces développements, menés avec des budgets limités, sont plus facilement maitrisables que s'ils étaient engagés simultanément sur un appareil nouveau.

Ensuite, en fonction des besoins du marché et dans le cadre général de la politique de produits, une intégration partielle ou générale est réalisée pour donner une machine revalorisée ou nouvelle.

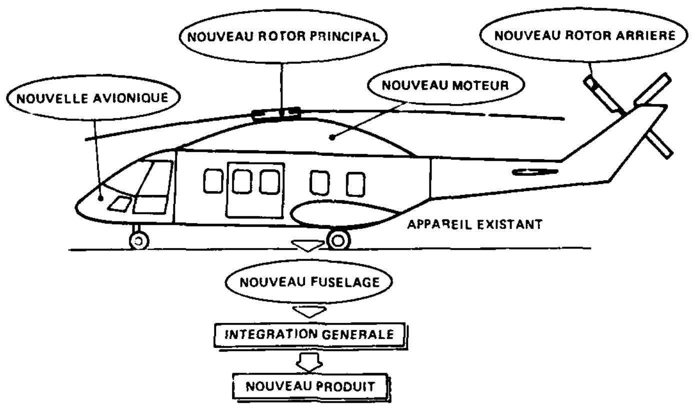

Figure 7 : REDUCTION DES COUTS DE DEVELOPPEMENT – DEVELOPPEMENTS PARALLELES

6.2 Procédure de conduite de programme de développement

Compte-tenu de l'importance des budgets engagés pour les activités de développement, de la durée des programmes et de la complexité technique toujours croissante, il est nécessaire de disposer d'une procédure de conduite de programme.

Par ailleurs, dans les marchés importants de développement tant nationaux qu'internationaux, une telle procédure est devenue contractuelle.

Elle est basée :

- Sur un découpage en phases de déroulement du programme
- Sur la mise en place de jalons formalisés permettant de maîtriser l'état d'avancement sous les aspects techniques, coûts et délais
- Sur une évaluation permanente des risques et la recherche de solutions pour les minimiser.

PHASES	DOCUMENTS / PRODUITS
ETUDES DE BESOINS	FICHE PROGRAMME
PRE-DEVELOPPEMENT FAISABILITE AVANT PROJET	DOSSIER DE PRE-DEVELOPPEMENT CHARTE D'EXECUTION DOSSIER DE LANCEMENT
DEVELOPPEMENT PREPARATION DEFINITION ETUDES REALISATION QUALIFICATION	PLAN D'EXECUTION DOSSIER DE DEFINITION PRELIMINAIRE LIASSE PROTOTYPE PROTOTYPES DOSSIER DE QUALIFICATION

INDUSTRIALISATION ET SERIE

Figure 8 : DECOUPAGE EN PHASES D'UN PROGRAMME DE DEVELOPPEMENT

Les grandes phases que sont l'étude de besoins, le prédéveloppement, le développement, sont séparées par des périodes d'examen et de décision conduisant à des autorisations de programme.

A partir des études de besoins, la fiche programme précise l'ensemble des objectifs techniques, économiques et calendaires à atteindre.

La phase de prédéveloppement est extrêmement importante car c'est à ce stade que sont évaluées les différentes solutions possibles, fixés les choix principaux, et établis les coûts prévisionnels et les délais qui deviennent des objectifs à tenir pour le développement complet. Ensuite, la phase définition projet :

- Fixe la définition technique (permet l'établissement de clauses techniques générales et de descriptifs techniques)
- Met en place un organigramme technique par taches
- Donne les plannings généraux du développement et de l'industrialisation
- Etablit les coûts de développement et d'industrialisation
- et affine le coût de série.

Cet ensemble devient alors la charte d'exécution.

Le dossier de lancement présente et justifie le programme à l'Etat-Major de la Division et à la Direction Générale pour obtenir la décision de lancement. Il contient les aspects commerciaux, techniques industriels et financiers.

Le plan d'exécution décrit l'ensemble des dispositions prises pour réaliser le programme conformément à la charte d'exécution et identifie les travaux et les responsabilités correspondantes.

Il rassemble :

- Le plan qualité
- L'organigramme technique
- Le plan de revues
- Le plan de fiabilité
- Le plan de maintenabilité
- Le plan de qualification
- Le plan de certification / homologation
- Le plan de gestion
- Le plan d'action commerciale
- Le plan de support d'exploitation.

En particulier, l'organigramme technique recense les travaux nécessaires à la réalisation du programme et définit une structure permettant le contrôle des coûts et des délais. Il s'appuie sur la décomposition arborescente de l'ensemble que représente le programme en ses divers constituants, qu'il s'agisse d'entités physiques ou de logiciels.

Cette procédure constitue un guide de pilotage, à la disposition des Directeurs de Programme, qui doit rester suffisamment souple pour s'adapter aux caractéristiques de chaque programme. Il est bien évident que les structures pour conduire un programme interne à faible budget doivent être plus légères que celles d'un grand programme national ou international et dans ce cas, il faut s'attacher plus aux principes qu'à la lettre de cette organisation.

6.3 Organisation des activités de développement

Sur l'organigramme Figure 9, on voit que toutes les activités de développement, Direction des études, Département réalisation prototype, Direction des essais, ont été regroupées sous une même Direction.

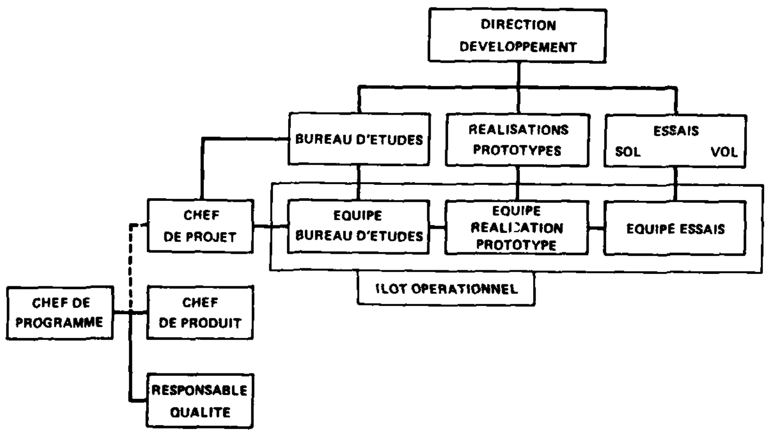

Figure 9 : ORGANISATION DES ACTIVITES DE DEVELOPPEMENT

La Direction du Développement est chargée d'orienter la politique technique de la Division et d'assurer les développements nouveaux au moindre coût et dans les délais les plus courts dans le cadre des objectifs fixés par la Direction des Programmes.

Le Chef de Projet, issu du Bureau d'Etudes, a, par délégation du Directeur de programme, la responsabilité de conduite du développement, de la définition jusqu'à la qualification, sur les plans techniques, coûts et délais. Il doit rendre compte des faits techniques à la Direction des Etudes, des faits techniques et des problèmes de coordination à la Direction du Développement et des aspects programmes au Chef de Programme.

Pour accomplir sa mission, le Chef de Projet dispose d'une équipe Bureau d'Etudes, d'une équipe réalisation prototype et d'une équipe essais, l'ensemble pouvant être regroupé à l'intérieur d'un ilôt opérationnel.

La responsabilité d'exécution des taches reste du domaine de chaque Direction fonctionnelle concernée.

6.4 Dispositions prises pour réduire les coûts et les cycles dans les différentes activités de développement

La Figure 10, donnant la répartition du coût des activités de développement pour les principaux programmes conduits à la Division Hélicoptères de l'Aérospatiale, montre que les pourcentages moyens de coût de développement se situent à :

15 % pour le Bureau d'Etudes
35 % pour la Fabrication Prototype
20 % pour les Essais sol
30 % pour les Essais vol

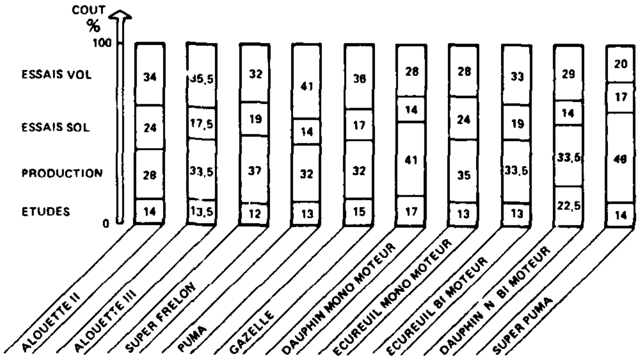

Figure 10 : REPARTITION DES ACTIVITES DE DEVELOPPEMENT

Bien que le Bureau d'Etudes participe pour une part assez faible aux frais de développement, il génere en fait les dépenses de fabrications et d'essais et il convient de faire des études de qualité si on veut réduire de façon substantielle les coûts de production et d'essais.

6.4.1 Bureau d'Etudes

Comme on peut le remarquer sur la Figure 11, 70 % de la qualité du produit dépend du Bureau d'Etudes seul pour des dépenses et un temps relativement faibles par rapport à l'ensemble du programme.

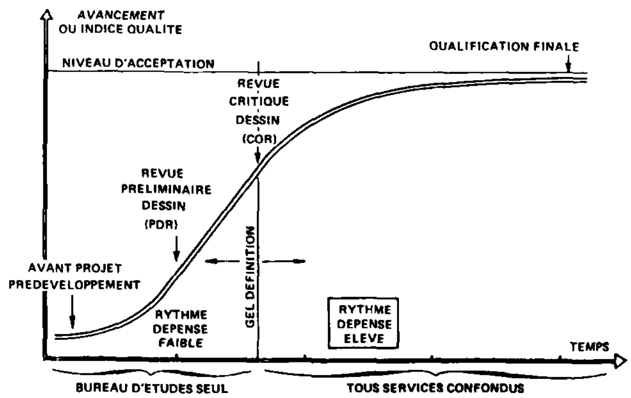

Figure 11 : LE COUT DE LA QUALITE

La réduction des coûts et des cycles d'études ne doit pas se faire au détriment de la qualité qui doit rester l'objectif prioritaire d'un Bureau d'Etudes. Une mauvaise orientation au départ entraîne toujours des modifications importantes et une inflation des coûts et des délais.

Le Bureau d'Etudes Hélicoptères de l'Aérospatiale s'est doté des structures et des moyens pour mieux travailler et faire bien du premier coup.

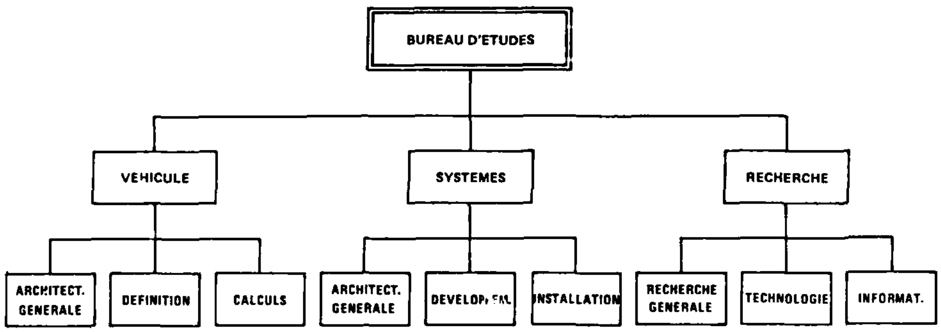

Figure 12 : ORGANIGRAMME

Des Départements d'Architectures Générales Véhicule et Systèmes ont d'abord été créés. C'est dans ces deux secteurs, dégagés des contraintes journalières, que l'on rencontre dans les équipes impliquées dans les lignes de produits, qu'est conduite la réflexion au stade avant-projet et prédéveloppement.

Comme nous l'avons vu précédemment, ce travail est extrêmement important puisqu'il fixe les choix techniques principaux, les coûts et les délais qui deviendront contractuels vis-à-vis du Chef de Programme.

Ensuite, pour la phase de développement, le Bureau d'Etudes a instauré le principe de travail dit en équipe intégrée.

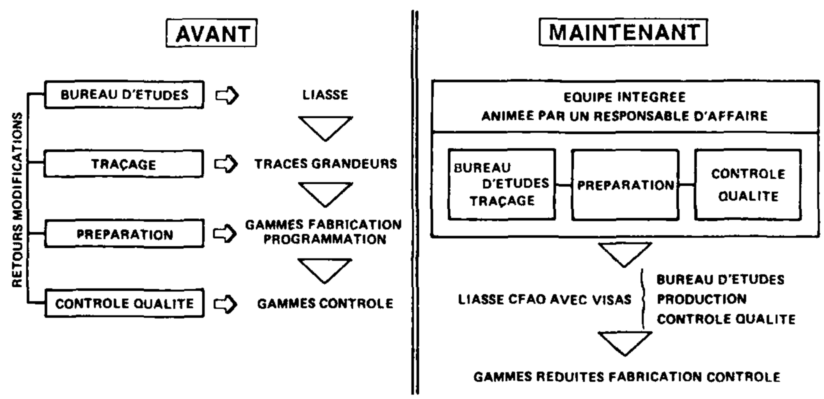

Figure 13 : TRAVAIL EN EQUIPE INTEGREE – ORGANISATION

Pour réaliser une tache bien définie, l'équipe intégrée regroupe le Bureau d'Etudes - Traçage, la Préparation et le Contrôle Qualité sous l'autorité d'un responsable d'affaire. Le responsable d'affaire est en liaison directe avec le Chef de Projet.

Avant la sortie du Bureau d'Etudes, les plans CFAO sont visés non seulement par le Bureau d'Etudes mais aussi par la Préparation Production et le Contrôle Qualité.

Cette organisation a permis :

- De responsabiliser les différents services au niveau de l'étude (visas obligatoires)
- De ne réaliser qu'un seul document informatisé sous la forme de dessins - tracés CFAO
- De systématiser les études d'analyse de la valeur
- De mieux adapter le produit aux moyens de production et de contrôle
- D'intégrer les besoins de production et contrôle sur les dessins (réserves d'usinage, programmation, ...)
- D'effectuer la préparation en amont avant la diffusion des plans
- De réaliser la programmation commande numérique automatique à partir du fichier CFAO.

Un contrôle final des plans avant diffusion a également été mis en place pour vérifier la qualité des dessins.

Toutes ces dispositions ont permis de diminuer notablement les demandes de modifications après diffusion des plans, et de réduire de façon très significative les coûts globaux et surtout les cycles études - production.

Des objectifs de – 15 % en coût et – 30 % en cycle sont tout à fait réalistes comme le montre la Figure 14 donnant les résultats du développement d'une modification importante de poutre de queue.

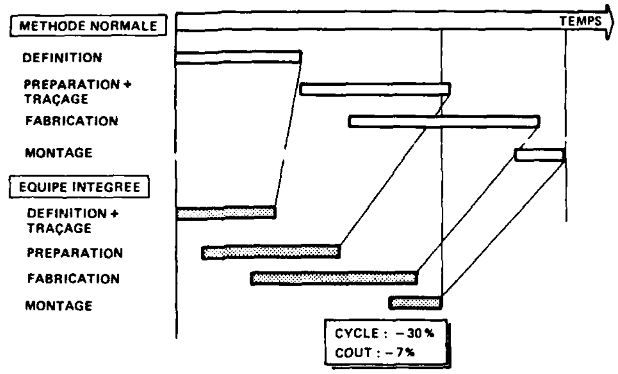

Figure 14 : REDUCTION COUT-CYCLE DE DEVELOPPEMENT – TRAVAIL EN EQUIPE INTEGREE

Dans le domaine très spécialisé des systèmes, le Bureau d'Etudes a profondément modifié sa méthodologie de développement.

Les systèmes antérieurs, dits juxtaposés, reposaient sur le fait que chaque fonction opérationnelle était exécutée par un équipement ou groupe d'équipements, et que l'interdépendance était très réduite.

Les spécifications à la charge du maître d'oeuvre étaient générales et se limitaient aux performances, interfaces et tenue à l'environnement.

L'affinement était en général conduit au cours de la mise au point en fonction des besoins ce qui entrainait déjà une inflation de modifications difficilement maîtrisable.

Aujourd'hui, les systèmes sont numériques et intégrés :

– Un nombre considérable de traitements sont concentrés dans un ou plusieurs calculateurs.

– Les fonctions de visualisations sont exécutées avec des équipements de visualisation multimodes et des postes de commande multiplexés.

– La grande majorité des échanges de données entre équipements est concentrée sur un ou des bus multiplexés.

Ceci, conjugué à une complexité de fonctions largement accrue, oblige l'avionneur à établir une spécification fonctionnelle globale pour parvenir à une spécification fonctionnelle détaillée des équipements autour desquels est construit le systeme intégré. Il est bien clair qu'une étude détaillée du système, morcelée par fonctions opérationnelles, et sous-traitée aux équipementiers, serait totalement incontrôlable.

Ces nouvelles taches imparties à l'avionneur rendent indispensable l'utilisation de méthodes et de moyens d'aide à la conception.

La méthodologie utilisée est celle du diagramme dit en V.

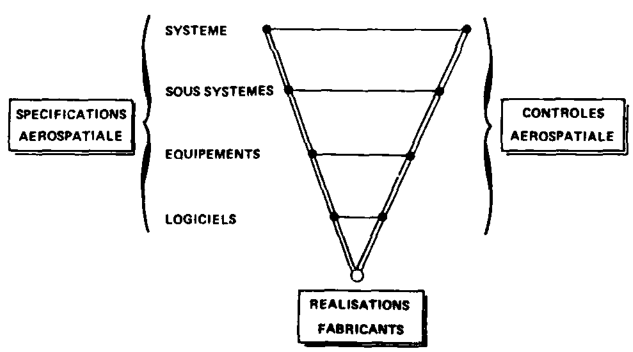

Figure 15 : METHODOLOGIE DE DEVELOPPEMENT SYSTEMES – DIAGRAMME EN V

Des spécifications sont écrites à différents niveaux : système global, sous-systèmes, équipements, logiciels. Apres réalisation chez les équipementiers, chaque niveau de spécification est contrôlé grâce à la simulation

Pendant la définition, il est possible d'effectuer des simulations en temps différé et de réaliser éventuellement des premieres modifications avant vol.

Cette démarche système permet une mise au point plus facile, la standardisation des fonctions élémentaires et la réduction sinon l'élimination des erreurs.

Ainsi, en phase de mise au point, il ne doit y avoir que des modifications mineures sans remise en cause fondamentale.

Pour faciliter le dialogue entre l'avionneur et les équipementiers, des moyens matériels et logiciels sont actuellement en cours d'élaboration sur le plan national pour utiliser un langage informatique commun.

Toutes ces nouvelles méthodologies s'appuient essentiellement sur l'informatique, domaine où un niveau d'investissement élevé a été maintenu depuis 15 ans.

La réalisation des dessins à l'ordinateur est généralisée de manière à n'avoir qu'un fichier unique utilisable par tous.

Des logiciels de calcul, de conception, de simulation ont été développés dans tous les domaines mécaniques et systèmes.

Des gains spectaculaires ont pu être ainsi obtenus en qualité et réductions de coûts et de cycles au Bureau d'Etudes, mais l'essentiel des gains apparaissent en fabrication et en essais.

6.4.2 Réalisation prototype

Les coûts et les cycles de réalisation prototype dépendent :

- De la conception réalisée par le Bureau d'Etudes
- Du circuit et des moyens de fabrication des pièces
- Des méthodes de montage
- De l'organisation des chantiers de modifications.

Si le Bureau d'Etudes doit concevoir le produit en vue d'une production en série, il doit adapter sa définition pour la phase prototype. Ce travail est réalisé au sein des équipes intégrées regroupant dessinateurs - préparateurs et contrôleurs en appliquant des règles simples :

- Découpage de l'appareil en tronçons pré-équipés
- Réutilisation de pièces existantes
- Elimination des solutions nécessitant des outillages sophistiqués
- Réduction des exigences de qualité des pièces
- Larges ouvertures pour faciliter l'accès.

En production, il vaut mieux perdre du temps sur les pièces élémentaires pour gagner en cycle global car la somme des optimums n'est pas forcément l'optimum.

Ainsi, un gain important en cycle est obtenu, par rapport à la méthode classique d'équipement après assemblage, en découpant les appareils en éléments modulaires pré-équipés, fabriqués en parallèle, et intégrés au stade ultime.

La réutilisation de pièces existantes est redevenue possible grâce à la technologie de groupe. En effet, devant des difficultés pratiquement insurmontables de recherche parmi des centaines de milliers de pièces déjà fabriquées, le projeteur avait une tendance naturelle à en créer de nouvelles.

Depuis deux ans, la Division Hélicoptères utilise la technologie de groupe grâce au logiciel SPIDER* développé à la Division Avions de l'Aérospatiale. A partir d'une codification à trente caractères, le fichier de pièces existantes est consulté pour rechercher des éléments identiques ou de même famille. En plus de la réduction du nombre de pièces nouvelles et d'une standardisation progressive, ce logiciel débouche sur la réalisation de gammes automatiques.

* *Systèmes de Production Informatisée D'Eléments Regroupés*

Au niveau de la définition des pièces élémentaires, le Bureau d'Etudes doit adapter la conception à des moyens de fabrication prototype sans outillages onéreux. Il doit par ailleurs éviter d'exiger une qualité trop élevée quand c'est inutile. Il faut naturellement assurer la sécurité, mais il est parfaitement admissible, pour un développement, d'avoir des potentiels limités.

L'accessibilité est toujours un sujet d'âpres discussions entre les gens de Production et de Bureau d'Etudes et conduit à un compromis raisonnable masse, coût de fabrication, facilité de montage pour une optimisation globale meilleure.

En ce qui concerne la fabrication des pièces prototypes, nous avons pu réaliser des gains spectaculaires.

D'abord en évitant les lancements trop importants en prenant quelques risques.

Ensuite en faisant la chasse aux temps morts.

La fabrication des pièces prototypes était insérée dans le circuit de fabrication cadencée où l'on constate en moyenne 1 % du temps en usinage et 99 % en attente (contrôle, stockage, ...).

Pour réduire ces temps morts, les pièces à chemin critique sont suivies à l'unité par un préparateur qui a la responsabilité de toutes les phases, préparation, lancement, suivi des étapes d'usinage jusqu'au montage. Les temps ont pu être ainsi divisés par 10.

Par ailleurs, une méthode de travail dite en «V.S.D.» (Vendredi, Samedi, Dimanche) est appliquée pour utiliser le parc machine de production série pendant le week-end. L'usinage est réalisé les jours de fermeture de fin de semaine alors que les phases interruptives, contrôle, réparations, se déroulent les jours ouvrables. Ce mode de travail permet :

- D'avoir un parc machine disponible à 100 %
- De diminuer les risques de perturbations extérieurs
- De mieux rentabiliser les moyens d'usinage.

Enfin, l'usinage sur machine à commande numérique, à partir des fichiers Bureau d'Etudes est généralisé en prototype. Les prix d'usinage ont pu être divisés par un coefficient de 5 à 10 par rapport à un usinage sur machine conventionnelle.

Deux exemples illustrent les résultats obtenus.

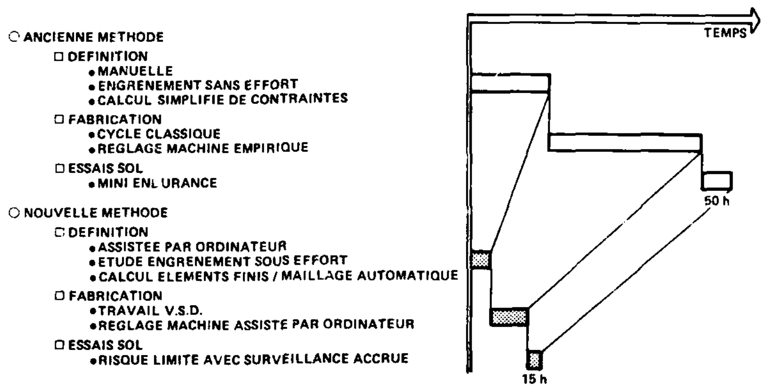

Figure 16 : REDUCTION DE CYCLE DE DEVELOPPEMENT COUPLE D'ENGRENAGES SPIRO-CONIQUES

La Figure 16 montre que le cycle de développement d'un couple d'engrenages spiro-coniques Gleason a été divisé par 3 grâce à l'informatique (conception, simulation d'engrènement, réglage machine par ordinateur) et le travail en V.S.D.

De même sur la Figure 17, on voit que le temps de développement d'une modification importante de boîte de transmission principale a été réduit de 30 % avec un cycle de fabrication divisé par 2, en effectuant la préparation en amont au sein de l'équipe intégrée et en travaillant en V.S.D.

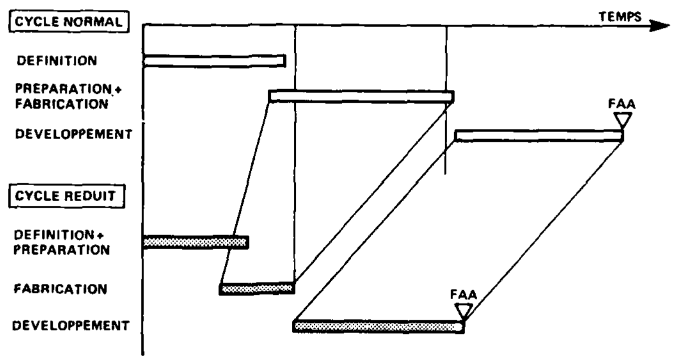

Figure 17 : REDUCTION DE CYCLE DE DEVELOPPEMENT BOITE DE TRANSMISSION PRINCIPALE SUPER PUMA REVALORISE

En phase de mise au point, les chantiers de modifications prennent aussi beaucoup de temps. Dans ce domaine également, grâce à des mesures d'organisation et en laissant plus de responsabilité et d'initiative aux équipes, des progrès significatifs ont été obtenus.

Une procédure rigoureuse de suivi des appareils en développement est d'abord indispensable si on veut éviter des surprises désagréables au moment des modifications.

D'autre part, les chantiers sont établis en commun entre Préparation et Bureau d'Etudes en établissant un programme de travail de base, logique et chronologique. La Maîtrise et le Contrôle avec l'aide du Bureau d'Etudes peuvent ensuite improviser pour occuper totalement le terrain et les espaces disponibles en s'écartant du programme initial.

Par exemple, le chantier d'équipement du DAUPHIN PANTHER est passé de 14 mois pour le premier appareil prototype à 10 mois pour le second, en identifiant bien l'appareil au départ et en laissant plus de responsabilité, de souplesse et d'initiative aux équipes.

La Division Hélicoptères Aérospatiale veut également entraîner ses fournisseurs dans cette campagne de réduction des coûts et des cycles.

6.4.3 Les Achats extérieurs

Lorsque l'on regarde la répartition des coûts d'un appareil, on s'aperçoit que la part de l'avionneur est relativement faible, de l'ordre de 20 % et que tous nos efforts auraient bien peu d'effets si nos fournisseurs n'accomplissaient pas les mêmes.

PARTS AEROSPATIALE/FOURNISSEURS

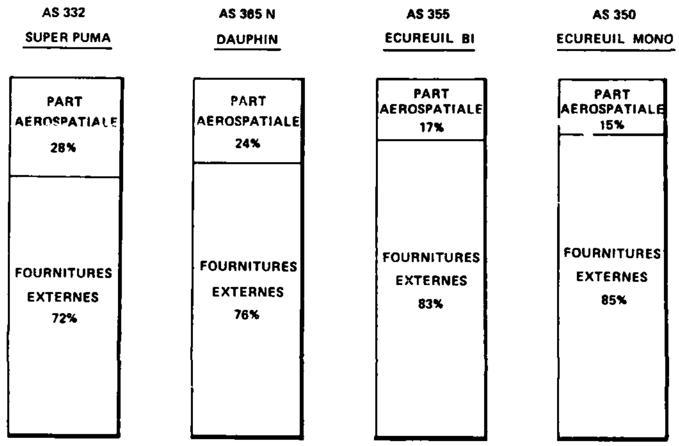

Figure 18 : PRIX DE REVIENT DE PRODUCTION

Il est très important d'établir une politique de coopération très étroite avec les fournisseurs afin qu'ils soient directement intéressés au bon déroulement des programmes.

A partir de spécifications du Bureau d'Etudes définissant les besoins en termes de fonctions et de contraintes mais en laissant le plus d'autonomie possible pour la conception du produit, un à deux fournisseurs par équipement sont choisis par la procédure appel d'offre.

Une fois le choix effectué, des relations de partenariat sont établies pour le développement et la série.

Les spécifications sont alors examinées entre le fournisseur et l'Aérospatiale (Bureau d'Etudes, Achats, Contrôle Qualité). l'Aérospatiale étant en position de conseiller.

Le financement est réparti en fonction des prestations pour les contrats Etat alors que les risques sont répartis suivant les responsabilités pour les développements privés.

Durant la phase de mise au point, c'est le fournisseur qui doit assurer les dépannages avec une assistance technique sur place.

Le niveau de rechange est également de sa responsabilité.

Par ailleurs, des études d'analyse de la valeur sont conduites dès le départ, sans trop pénaliser le développement, en visant plutôt la définition série.

Grâce à une étroite collaboration, l'Aérospatiale souhaite entraîner ses fournisseurs dans cette guerre contre les coûts et les cycles en leur faisant profiter de son expérience.

6.4.4 Les Essais

Bien que plus difficiles à maîtriser en raison de leur caractère souvent aléatoire, il est possible de réduire les coûts et les cycles d'essais avec une bonne organisation et des méthodologies modernes malgré la complexité croissante des systèmes embarqués et l'augmentation des performances des machines.

Le rattachement de la Direction des Etudes et de la Direction des Essais à une Direction du Développement permet de mieux coordonner les programmes d'essais et d'obtenir un arbitrage en cas de désaccord.

Les installations d'essais, qui jusqu'à maintenant étaient montées après la sortie du prototype, seront à l'avenir installées en temps masqué en fin de réalisation. Un gain de 1 à 3 mois est attendu suivant l'importance de l'installation. D'autre part, une chasse à l'essai inutile est lancée. En effet, il n'est pas rare de recommencer un essai à cause d'un programme incomplet ou d'un matériel non conforme. Il faut aussi faire le maximum d'essais au sol plutôt qu'en vol.

Aujourd'hui, tous les problèmes aérodynamiques sont étudiés en soufflerie puis vérifiés en vol.

Toutes les fonctions systèmes sont analysées sur simulateur avant le premier vol. Ensuite, pour la mise au point sur appareil, le maximum de paramètres est enregistré en vol. Au sol, une sélection des paramètres influants est effectuée et les autres sont stockés pour traitement éventuel. Les paramètres influants sont affinés sur simulateur puis vérifiés en vol.

La Figure 19 donne le bilan comparé de la mise au point de calculateurs de vol numériques. De 1981 à 1985, le nombre d'heures de vol a été divisé par 3 et la durée par 3,5 grâce en grande partie à la simulation.

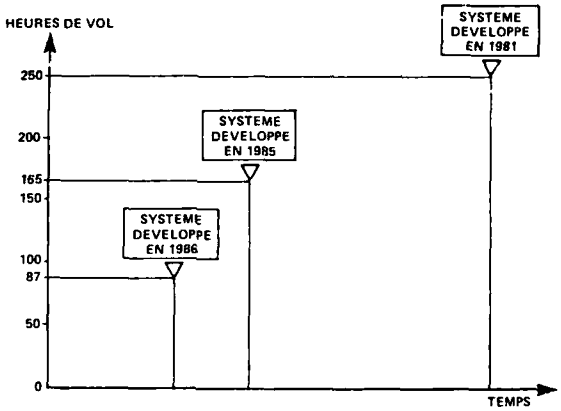

Figure 19 : CALCULATEUR DE VOL NUMERIQUE — BILAN COMPARE DE MISE AU POINT

Tout ce qui est fonctionnel avec un modèle représentatif est maîtrisé par la simulation, mais la limitation des coûts, des moyens de simulation, oblige à restreindre le nombre de modèles et à conserver un nombre d'heures de vol assez élevé. Il faut trouver le bon compromis.

Il faut aussi pouvoir exploiter rapidement les enregistrements effectués en vol ou au sol. Un logiciel d'exploitation d'essais permet aujourd'hui de stocker, de gérer et de traiter les paramètres d'essais dans un temps extrêmement court.

CONCLUSION

La pression de l'évolution technologique, la complexité croissante des systèmes, l'augmentation des performances, les exigences de plus en plus importantes des utilisateurs dans les domaines du confort, de la sécurité, de la fiabilité, de la rentabilité entraînent inévitablement une tendance inflationniste des coûts et des cycles de développement.

Depuis plus de trente ans, l'industrie française d'hélicoptères a mené une politique de développement ayant conduit à d'excellents résultats.

Vers les années 1970, elle a déjà su effectuer les redressements nécessaires devant une augmentation démesurée des coûts et des cycles de développement en créant des îlôts opérationnels.

Aujourd'hui, il faut prendre de nouvelles dispositions pour continuer à développer de nouveaux produits dans des contraintes de coût et de délais raisonnables, compatibles avec les moyens de financement disponibles et malheureusement limités par la morosité du marché civil et l'absence de marchés militaires substantiels.

Une politique prudente consiste à conduire des développements probatoires utilisés ensuite ou non pour faire évoluer les appareils existants ou créer des machines nouvelles.

En fonction des besoins du marché, la méthodologie de conduite de programme adaptée permet de réfléchir et de faire les bons choix techniques et économiques avant la décision de lancement, et de contrôler ensuite, à chaque étape, l'avancement du projet par rapport aux objectifs.

Pour mieux coordonner les activités de développement, le Bureau d'Etudes, la Réalisation Prototype et les Essais ont été regroupés sous une Direction du Développement.

D'autre part, au sein des différentes activités de développement, l'organisation, la méthodologie, les moyens ont été repensés pour améliorer l'efficacité.

Le Bureau d'Etudes s'est doté de départements d'architecture générale véhicule et systèmes pour préparer les développements de demain.

Le travail en équipe intégrée a été instauré pour permettre de traiter la préparation fabrication et contrôle en même temps que la conception. Une utilisation de plus en plus poussée de l'informatique a été engagée.

Enfin, des actions vigoureuses ont été entreprises pour améliorer la qualité et faire bien du premier coup.

En Production, l'informatique et le travail en V.S.D. (Vendredi, Samedi, Dimanche) a permis des gains de coûts et de cycles très importants. Le temps de réalisation des chantiers a été fortement réduit par une utilisation optimale des espaces et une meilleure organisation tout en laissant plus d'initiative aux équipes.

Une action de motivation des fournisseurs est également en cours.

Dans le domaine des essais, les essais en vol tendent a être réduits au profit des essais sol, des essais en soufflerie et de la simulation.

Toutes ces dispositions permettent d'obtenir une meilleure utilisation des capacités de développement en réduisant de façon significative les coûts et les cycles.

Il ne fait aucun doute que ces efforts doivent être poursuivis pour s'adapter en permanence à l'évolution de la technique et de l'environnement économique mondial, et produire économiquement, au bon moment, les machines les plus efficaces et les plus rentables.

THE INFLUENCE OF INFRASTRUCTURE ON THE COSTS AND TIMESCALES OF COLLABORATIVE PROGRAMMES

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INTRODUCTION

International collaboration is an increasingly important method of launching major new aircraft projects. In the military context there are substantial political advantages and also military benefits - not least as a consequence of inter-operability - but the effect on costs is often a major consideration when deciding to pursue a collaborative rather than national project. The most obvious attraction is the sharing of development (and other non-recurring) costs - particularly as these occur in the near future where budget pressures are often highest; moreover, the greater production volume should also lead to reductions in unit price. However, experience with collaborative aircraft programmes to date suggests that there are also some more subtle effects operating which effect total programme costs and thus change the financial and operational benefits to any single nation.

Direct comparisons between a collaborative programme and an identical national alternative are obviously impossible, so to draw conclusions about the effects of collaboration on costs it would be desirable to compare the average of a large number of national programmes with a similar number of international collaborative programmes of the same type. Unfortunately there have not yet been enough collaborative aircraft programmes to permit such statistical analysis - indeed the programmes which have taken place have often differed in their management arrangements. The views expressed in this paper therefore reflect only current - largely personal - views obtained by comparing a few international projects with what might have been expected to happen on the basis of statistics for national programmes. This process has some inevitable uncertainties and leads primarily to qualitative rather than quantitative assessments of the effects. Moreover the national data base used (the UK in this case) may not be directly applicable to other nations. For these reasons the views expressed here are purely those of the author and should in no way be taken as a formal UK view. Nevertheless, despite all these qualifications, it may still be useful to illustrate the scale of some of the general effects by comparing a hypothetical collaborative fixed wing combat aircraft programme and an equally hypothetical national alternative. The approach taken is to consider the various stages of the project in their natural sequence and comment on the factors involved in each phase; it should then be possible to indicate how changes in the Infrastructure of Industry and Government organizations might help to reduce the costs of collaborative programmes still further.

Having used the words collaboration or collaborative so much, it is desirable to define them clearly. Collaboration, in the sense in which it is used in this paper, implies a genuine partnership between equals. Even where financial contributions are not equal, international collaboration usually involves equal power of decision in the collaborating nations. This arrangement is very different from international sub-contracting, or an agreement to share a market (with each nation making and selling its own different but complementary products), since these both ensure that decision making is retained at one location. Collaboration between equals is, of course, now becoming established in the commercial/civil field as well as in the military area, but this paper focuses on military aircraft collaboration with particular emphasis on the European industry.

DEFINITION OF THE PROGRAMME

The bulk of the Life Cycle Costs of any programme are broadly determined by the decisions taken during and just after programme definition. This phase is therefore of crucial importance. The decisions involved - to have a programme, the size, speed and capability of the aircraft etc - may not be very detailed but they set a pattern which determines the difficulty of the technical task and the cost consequences.

Definition of any programme, collaborative or otherwise should start by considering the target to be achieved. For a military programme this involves consideration of threats from potential enemies. In a collaborative programme involving nations who are widely separated geographically it is not, perhaps, too surprising that different perceptions of the threat can arise. These differences may lead to requirements for aircraft which vary from nation to nation and the effect can be exaggerated by different military traditions, philosophy and experience. As a consequence, in a collaborative programme, there is often a need to reconcile different appreciations of what the aircraft might need to do and, therefore, how it should be designed.

Whilst it would be a gross oversimplification to suggest that the outcome of negotiations is a requirement to fulfil, simultaneously, all the nations objectives, there is certainly a tendency for the joint requirement to be more demanding than any nation would propose for a purely national programme. Of course this enhanced capability has significant advantages for military operations since it permits much greater operational flexibility. Nevertheless such increased capability entails a greater development and production cost. Moreover there is a danger that - to obtain agreement - the issues may be "blurred" so that unresolved differences are left in the specification. This then can cause not only problems during development but also the undermining of a taut fixed/firm price contract. The magnitude of the cost increase arising from the enhanced requirement depends on the capability of the alternatives which would have been purchased if collaboration had not taken place. In the case of those Tornado nations, who were originally expecting to buy a single engined aircraft, the cost increment associated with acquiring a two-seat, twin engined aircraft might have been 30% but in general the increase would be much less.

At first sight it might seem likely that the development costs for a more complex aircraft would be increased (by the extra complexity) more than the corresponding increase in production cost. (Several capabilities would need to be developed simultaneously - but the production task would still be to produce an aircraft to a well defined set of drawings). However, statistical analysis of past national programmes suggests that the ratio of development cost to unit production cost for a given component (airframe, engine, etc) is largely independent of the complexity of the design. On this basis any effect of extra complexity which raises development costs is also likely to raise, the much larger, production costs by a similar percentage.

Apart from the effect on costs the elaboration of international requirements (over purely national ones) could be expected to lengthen timescales. However, my colleague Philip Pugh has shown, Reference 1, that the statistics - such as they are - do not support this view. The International programmes do not stand out from the general trends of UK National Programmes. Admittedly the scatter on national statistics is very large and it may be that significant trends are present but will not be revealed until there are enough collaborative programmes to analyse properly. Certainly there is a widely held view that international agreement can take longer than national agreement - if only because there are more opportunities for elections to intervene and for budgetary problems to surface (if delays occur at this stage of the project the main cost effect - waiting time of relevant staff - may well appear as an overhead on current projects rather than as a direct charge to the new project). Of course any extension of the definition phase could also have benefits; either in permitting better consideration of the requirement so that development begins with a clearer understanding of what is required and how it is to be met (which will almost certainly reduce nugatory work and expenditure) or by allowing more time for parallel developments in technology to reduce risks in the programme (provided the specification is not also upgraded); at the same time delays increase the risk of obsolescent aircraft being produced.

IMPLEMENTATION OF THE PROGRAMME - DEVELOPMENT

Having agreed to proceed with a common programme towards a (basically) common end there are still a number of features which inflate the total cost of a collaborative programme relative to a purely national alternative aimed at meeting the same specification. Firstly agreement on the common programme often excludes some features of the weapon system which continue as "National Variants" - ie peculiar to one particular nation - either as a means of satisfying some particular operational requirement or to ensure commonality or compatibility with other equipment already in the inventory. Secondly (and partly deriving from the National Variant requirements) there is usually a demand to have flight test centres in each of the countries involved; this also tends to require additional hardware in the test programme generally. The costs of some of the activities in a collaborative development are, therefore, multiplied by the number of participants but this factor applies only to a small part of the total. A model of the airframe development programme has been used to assess how the additional complexities of collaboration influence total development costs. Each facet of the development was assigned a "collaboration factor" ranging from the number of participants (n) (for activities like provision of flight test facilities), to unity where no extra costs were appropriate. This model was essentially the normal model used for evaluating the cost of national programmes but with the addition of the collaboration factors. The model has made fairly accurate estimates of the actual outturn of the few international programmes to which it could be applied. Removing the collaboration factors (and using the model as it would normally apply for a national programme) then provided a means of quantifying the average "collaboration factor" on development of airframes. Broadly speaking the results were consistent with the average cost multiplier being about equal to the square root of the number of participants. This "square root law" is of course of very limited applicability and should not be used for serious estimating - particularly where the number of participants may be large - but it indicates the scale of likely cost increases. Airframe costs were selected for the comparative exercise because the historical record is usually less confused by changes of requirement during the development programme than either engines or avionics. The later parts of this paper consider possible ways of reducing the "collaboration overhead" so it is appropriate here to indicate some of the factors which help to make up the cost increases. Furthermore specific, comments appear in References 3 and 4.

Firstly, there has already been reference to the requirement for more design and management teams at widely separated locations and expecting them to work closely. True collaboration has sometimes been defined as being between groups of people who have the ability - although not necessarily the resources - to do the whole task for themselves. Under such circumstances there is always a need for close liaison which gives rise to travel costs, time wasted during travel and delays due to arguments about the way ahead. Such arguments can arise not only from different design rules and experience in each of the companies - which are almost inevitable - but also from a less defensible variety of professional chauvinism known as the "Not Invented Here" syndrome.

Most of these effects arise in any collaborative programme whether it involves several nations' industries or whether the collaboration is between firms within a single nation. However in an international programme there can also be a further level of controversy arising from national industries acting as advocates for their respective air forces to pursue particular operational requirements which may have been only loosely covered in the specification. If an impasse is reached at company level and the dispute is referred to officials for resolution there is, therefore, a good probability of further intense argument and delay. The outcome of a technical problem in development may well therefore be a decision to pursue parallel "get well" programmes in 2 or more nations - simply as a means of achieving agreement on a way forward.

Finally, in the international development programme it is necessary to recognise that - on specific tasks - not all the participants are as capable as the more experienced companies. Indeed, since one of the objectives set by some nations is to acquire technology which their industry does not have, it is likely that such differences in capability will occur. These differences in capability can cause cost increases by requiring new facilities, which find their way back into total programme costs via the overhead structure, by lower productivity on specific tasks and by demanding uneconomical sub division of work on equipments or components. Clearly equity suggests that the nation requiring the technology should pay the extra costs but accounting practice seems to militate against this being achieved easily. In summary the extra costs of developing a collaborative military aeroplane relate to:

a. additional variants;

b. additional hardware for testing;

c. additional interfaces between design teams;

d. additional travel and transport - including the cost of lost time;

e. parallel developments;

f. costs associated with a nation acquiring technology new to its industry but available in the partner nations.

The effects of collaboration on development timescale depend on the resources assigned to the programme. Since more resources are available, the effects may well be small and indeed such statistics as are available do not permit identification of any significant 'ifferences between national and collaborative programmes.

PRODUCTION

Most aspects of the production process are organized in multinational programmes so that there is only a single work centre for each item. The main exception to this principle has been final assembly (which usually represents a very small proportion of total production cost). In general, it has been the practice for each partner to assemble the final article and this increases production costs due to multiplication of final assembly tooling and hangar facilities. However this small increase in cost is more than compensated by reductions in tooling cost - due to sharing and in unit cost which arise from the "learning" process by which repetitive production of identical articles leads to cost reduction as machine operators and their management learn how to do the job better as time progresses.

A typical "learning curve" for airframe production shows that an increase in production number by a factor of 2 can reduce the unit cost by up to 20% (the actual factor depends on many variables including the degree of automation and the efficiency of the company management). However this rapid learning is usually only experienced in the early part of an airframe programme. Later parts of the programme may only benefit by about 10% for every doubling of the quantity and when other parts of the weapon system are also considered (raw material costs, equipment, avionic costs etc and allowance is also made for non-common variants the overall average saving on unit costs tends to reduce to only about 5% for each doubling of the number of units involved. Of course a reduction of 5% on the cost of a $20M aeroplane is well worth having! However it should be remembered that the cost base, from which this reduction is being obtained, is that appropriate to the more complex aircraft agreed at the definition phase. Thus, provided most of the manufacturing is not duplicated and the achievement of highly integrated system is not hampered by the demands of work sharing, the overall effect on production costs of a collaborative programme, with a quadrupling of the numbers produced, should be small. Indeed there may well be no significant change in cost

relative to a national production of an alternative aircraft unless budgetary problems in one nation force a slow down of production t· the point where the industry resources are underemployed or unless one or more of the partners is less efficient (more expensive) than the others.

IN-SERVICE PHASE

The in-service component of the Life Cycle Costs (LCC) of an aircraft are a very significant fraction of the total LCC - usually substantially more than half. It might seem therefore that the predicted costs of this phase should be the dominant factor in determining not only which aircraft to buy but also how a new aircraft should be designed. In practice some of the costs are largely independent of detailed aircraft design (eg crew training and many overhead costs) but other factors such as reliability and maintainability are both important in determining costs and are also highly influenced by the actual engineering designs. The impact of collaboration on these costs is extremely difficult to identify. Each nation operates its aircraft according to national practices and uses up spares and maintenance man hours depending on the engineering design - not on the contractual arrangements for building the aircraft. Some increases in the use of spares and maintenance man hours is likely to arise as a consequence of the greater complexity of the international aircraft but at least the cost of major spares should be offset by a reduction in price arising from the greater volume being produced. Provided that compromises between national requirements, agreed at the definition stage, do not shorten the life of the weapon system and its components, the detailed attentions of several Air Forces and their procurement agencies can influence the design in favour of good reliability and maintainability to ensure no great differences between the cost of supporting a collaborative aircraft and a national alternative. Indeed Tornado R&M costs - as seen by the UK - seem to lie in the range predicted by extrapolation from previous national aircraft projects. One further area where in-service costs might be affected by collaboration relates to up-date programmes. Since the length of a development programme is usually comparable with the time between successive generations of avionic technology there is often a desire to upgrade at least the avionic requirements either during the main development or during the operational phase. In a national programme a substantial part of this "specification growth" is often incorporated during the main development. In a multinational programme there are more constraints and much of the updating development may well be postponed to the operational phase of the project. This increases the in-service costs, particularly if the development can then not be collaborative.

COST COMPARISON

So far this paper has concentrated on the qualitative effects which occur, but to put these effects into a more numerate form an actual hypothetical example is perhaps worth presenting. It should be emphasized that this is not a "typical" comparison (since there are large differences between programmes or even between the relative positions of individual nations in a single programme); it is purely illustrative.

The comparison is made between a 3 nation collaborative programme which is 10% more complex than the national alternatives with which it is compared. The overall increase in cost due to collaboration on development could amount to about 60%, split equally between the cost of extra programme items (more variants, more test specimens, more test hours etc) and management additions (liaison, parallel solutions etc). In each case the nation is expecting to buy 250 aircraft and in the collaborative programme the share is taken as one third. The figures are shown on Table 1.

	ARBITRARY UNITS			
	NATIONAL	COLLABORATIVE (TOTAL)	COLLABORATIVE (33% Share)	IDEAL COLLABORATIVE (33% Share)
Airframe Development	500	880	293	
Engine Development	400	704	235	
Avionics Development	600	1056	352	
TOTAL DEVELOPMENT	1500	2640	880	500
Airframe Production	1250	3750	1250	
Engine Production	250	750	250	
Avionics Production	1000	3000	1000	
TOTAL PRODUCTION	2500	7500	2500	2125
Support Including Overheads	6000	18000	6000	5600
GRAND TOTAL	10000	28140	9380	8225

TABLE 1 COST COMPARISON

In this example the saving over the life of the aircraft is just over 5% but it should be noted that there is a very substantial saving in the development phase (almost half) and this saving is of course achieved in the earliest years of the programme where budgetary pressures always seem to be tightest. The saving on this hypothetical programme (620 units) could however be considerably increased if better governmental and industrial arrangements could be achieved. Assuming "ideal" collaboration in which the aircraft definition and programme implementation do not suffer from increases in complexity, a further saving of 1150 units could be envisaged. This arises not only from a further reduction in development costs but also a 15% reduction in production costs by elimination of the national variants and enhanced capability demanded by requirement compromises. There is a corresponding reduction in spares costs and some reduction in maintenance manpower.

A reasonable target for improved management seems likely to be about half this further increase ie the total saving would be an approximate doubling of the 620 units calculated above to represent savings achieved by past collaborative practices. Such an improvement should help to increase "third party" sales (which may otherwise be inhibited by the cost of extra complexity) and thus produce still further savings by increasing the total number of units produced.

IMPROVED INFRASTRUCTURE

The particular features which demand attention if the efficiency of collaborative programmes is to be improved, are the agreement on requirement (essentially a government responsibility) and how the requirement is to be satisfied (ideally an industry responsibility) these features can be influenced by the infrastructure of industry and governments ie by the structure, organisation and management of the various agencies involved.

An improvement in the agreement of requirements will be difficult to achieve without some permanent group of military officers discussing openly the basic strategic and tactical thinking and even the intelligence reports which support some of that thinking. Such a Joint European Air Staff (JEAS) has already been suggested by Brian Young (Reference 4) and its purpose would be to prepare the ground long before there was a plan for an actual project. The intention would be to harmonize views on, for instance, the missions which would be needed to combat the threat, the intensity of peacetime training, to what extent a multirole capability would be required and even whether the optimum solution to the threat was an aircraft or a missile. If agreement could be reached on the basic issues a project requirement could evolve naturally and lead to a single design. This contrasts with the past practice of harmonization by trying to define the aircraft design and performance (mass, speed, turning capacity etc) to cope with different operational concepts. To be effective the JEAS would need to have access to technical advisers and these also should be organised multinationally. One possibility would be to make use of the SHAPE technical centre. Eventually this might lead to a single European multinational procurement agency but such an arrangement would be most unlikely without a major move towards political union in Western Europe. Nevertheless the establishment of permanent multinational organizations to allow requirements to evolve in common without the confrontations inherent in "negotiation" at a later stage on a specific project should be practical even without total political union. Staff - particularly Air Staff - would need to be assigned for a few (say 3) years at a time and would gain from the experience of discussing strategic thinking, with their colleagues in other nations, without project pressures. However even this sort of structure would need a major political initiative and it might be more realistic to consider how a change in industrial infrastructure could contribute to reduced collaboration costs and, perhaps, also help to harmonize military perception of the aircraft required.

One fundamental reason for high industrial costs in collaborative programmes is that although the total life of a collaborative aircraft project may be 40 years, the activity is seen as but one part of the operations of the various national companies involved. Although the partners often set up a joint company to oversee the project, direct control of the resources involved is retained by the partner companies; the joint company is an arrangement for the one project alone - just a small offshoot of the main company. Inevitably, therefore, each national firm tries to retain a total design and manufacture capability in case there is a need to collaborate with other partners on other projects or to do a single company development. This means that for a new project there is often the need to acquaint new partners with each others practices, strengths and weaknesses - indeed how to trust the strangers.

One possible route to improved arrangements would again be to emphasize the permanence of international collaboration by setting up permanent consortia by formal mergers of companies or divisions from the major European Aerospace nations. These consortia would then have direct control over the work forces involved in the project even though their shares would still be owned by the national companies. Indeed some national companies might well be involved in more than one consortium since to hone efficiency there should be at least 2 competing consortia. The existence of powerful, permanent, consortia would have several effects; firstly it would remove most of the inefficiencies associated with putting together a new group of companies for each project, secondly it would permit design and manufacture of specific components (wings, front fuselage etc) to be allocated permanently to one particular location so that conflicts between equally capable design bureaus would diminish and thirdly the presence of multinational aerospace consortia - each with a single industrial view

rather than individual companies responding to national preferences - would be likely to influence the various Air Staffs and produce some convergence of requirements. Finally these consortia would have the strength to comp ete, or collaborate, with US companies on an equal footing.

To make such consortia acceptable to all the European governments, as a means of providing both employment and military hardware, they would probably need to have a wide base including representative groups from at least all the major European aerospace nations. However there would also be a need to make the consortia acceptable to industry so there would have to be adequate incentives to create such multinational companies. The association would need to be voluntary rather than forced if efficient operations were to be achieved.

If this sort of arrangement is seen as desirable and efficient what actions could be taken to realise it? Firstly firms which have already been working together should be encouraged to continue, not only on defined projects but - perhaps by means of demonstrator programmes - on future technical concepts which are expected to be needed in future. Secondly these firms should be invited to draw in - at least on the demonstrator programmes - other significant firms in nations not represented in the current groupings, so that the group would be acceptable to a wider spectrum of European governments. As a means of achieving this a European Advanced Projects Authority could be set up to fund and manage the preparation of technology and thus perhaps influence the industrial groupings and the Air Staffs coordination. Moreover the availability of demonstrator funds on a European basis would not only enable specific aircraft, engine or avionic technologies to be explored in a realistic way, even before the feasibility stage of projects but could also focus attention on the manufacturing technology infrastructure. Innovations in manufacturing are often heralded as likely to decrease costs but sometimes the reality is quite different, thus the demonstration of production methods may be just as important an element of risk reduction as demonstrating equipment performance and durability. It is perhaps worth emphasizing that the funding of demonstrator programmes should not be seen as an increase in total costs but rather as a transfer of funds from project to pre-project activities. The likely consequences of demonstrating a realistic total aircraft (and a viable cheap manufacturing route) are a reduction of development costs and an increase in reliability and the other "ilities" at the time of entry into service thus giving substantial savings in whole life costs. Clearly the magnitude of the funding for demonstrators needs to be judged carefully in relation to the likely financial benefits but, ideally, technology demonstrations should be followed by competitive prototypes, to reduce risk before committing to full scale development.

The incentives for Governments to follow this route are partly financial (to save money) and partly to encourage interdependence and political harmony, but what are the incentives for industry? It might seem that a promise from European governments to buy military hardware only from suitable consortia would be useful. However such a promise would be close to applying coercion and in any event would be against the policy of allowing competition with American or other foreign products. The main incentive must therefore be the commercial judgement that an efficient European industry is likely to be able to sustain itself better in the long term than an inefficient one, particularly in competition or collaboration with US companies. There would also be some incentive if the demonstrator funding was initially both substantial and enough to cover 100% of industry's costs.

Finally improvements to infrastructure can be made within individual companies by attention to detailed management. In many cases this requires only the application of concentrated thought to expose weaknesses in past practices, but this process can be helped by modelling on a computer the companies operations. Computer modelling is being used increasingly to estimate the performance of aircraft or equipment, their structural strength (and hence life) or to simplify design and manufacture processes (CAD - CAM) and these innovations can in principle reduce the work content in aircraft development programmes. However modelling can be extended further to cover not only processes (casting techniques for instance) but also shop procedures, assembly techniques and their attendant costs; indeed almost all the activities within a company. By these techniques companies can gain a better understanding of where costs arise and how they might be reduced. Indeed it may be possible with such techniques to achieve significant savings on collaborative projects by understanding - in finer detail - the sources of the collaboration factors.

All these proposals for changing infrastructure are speculative so, if they fail, how can the cost benefits of collaborative programmes still be reduced below those levels currently applying? Assuming that no major change in infrastructure is possible, the responsibility for keeping costs down must remain with the national and international project offices; to recognise the hazards of extensive argument and needless official attention to fine detail decision taking while ensuring that industry has a clear task in front of it, well specified, well costed and realistic in terms of technical performance and timescale. In this context the most important element will be to begin only those programmes which have low risk as a consequence of the fact that the specification is closely matched to the level of technology which has already been demonstrated. In this way the probability of wasteful arguments and parallel "get well" programmes is reduced.

CONCLUSION

International collaboration can give substantial financial advantages - particularly in development - but there are features of past programmes which have also given rise to increased total costs. This has reduced the advantage in terms of whole life costs to a relatively small (but useful) percentage. No general assessment of the benefits is yet possible since there are insufficient, similar programmes on which to conduct statistical analysis - each programme proposal needs to be judged on its merits.

Although perfect collaboration, with no additional costs, is unlikely to be achieved there is room for a substantial additional saving to be made in comparison with those achieved to date. One possible means of making these extra savings would be by setting up permanent collaborative institutions in industry and between Governments.

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Another aim of this symposium was to encourage others in the nontechnical area to join with the technical people in attacking these problems, showing what technologies can do to reduce development time and cost growth, and by highlighting key areas that must be addressed to reverse the trend. The final recommendation of the symposium was to make sure that military and government leaders get this message. Keywords;

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